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Estimation of a risk profile to operatives and the public from motorway hard-shoulder incursions

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ESTIMATION OF A RISK PROFILE TO OPERATIVES AND THE PUBLIC FROM MOTORWAY HARD-SHOULDER INCURSIONS

By
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ABSTRACT

This project focuses on the risk to the operatives and the public arising from hard-shoulder incursions on motorways, which are defined as the temporary violation of this lane by a vehicle travelling on the nearside lane. Even though interest has been raised around safety when stopping on the hard-shoulder, there is no significant research conducted to investigate and quantify this risk.

In this EngD project, motorway hard-shoulder accidents were investigated individually from the main traffic lanes to explore the factors affecting their severity and likelihood and identify potential differences using discrete choice and time-series modelling techniques. Based on the safety triangle theory, it was assumed that eliminating the contributory factors for injury accidents would also minimise the risk of hard-shoulder incursions, which were used as a risk indicator. An observation-based survey was conducted to gain initial knowledge on the frequency of incursions within a motorway stretch and also basic conditions that may affect the severity as well.

Further to the survey, in order to collect hard-shoulder incursion data automatically, potential vehicle detection solutions were investigated. A radar sensor-based system was identified as the most suitable for this purpose and was adapted to suit the project's requirements. The sensor was installed on a motorway site, following a series of requirements to ensure safe and effective deployment. The data collected from the radar sensor were processed to minimise the errors and then corresponded to the traffic related and environmental data available for the same period of time.

Using the Generalised Linear Autoregressive Moving Average model, the final models developed provided the factors that mostly affect the occurrence of hard-shoulder incursions. The main factors are temperature, humidity, traffic composition and average speed on the main carriageway. Using these models it is possible to quantify the risk and forecast when this will be minimised at a particular motorway section at any time. The risk is estimated according to the explanatory variables proposed, by inputting the predictions of these conditions in the model. This model is a tool that may then allow the operatives to be deployed on the network in the safest manner, according to the levels of tolerable risk.

KEY WORDS

Motorway safety, Hard-Shoulder Incursions, Risk modelling, Radar sensor

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USED ACRONYMS / ABBREVIATIONS

AIC	Akaike's Information Criterion
ALR	All-Lane Running
ARIMA	Autoregressive Integrated Moving Average
BIC	Bayesian Information Criterion
CCTV	Closed-Circuit Television
CNDR	Carlisle Northern Development Route
DBFO	Design Build Finance Operate
DfT	Department for Transport
DMRB	Design Manual for Roads and Bridges
EngD	Engineering Doctorate
FPE	Final Prediction Error
GB	Great Britain
GDP	Gross Domestic Product
HGV	Heavy Goods Vehicle
HQIC	Hannan and Quinn Information Criterion
HS	Hard-Shoulder
H&S	Health and Safety
HSE	Health and Safety Executive
ICC	Intra-class Correlation Coefficient
ISU	Incident Support Unit
LFS	Labour Force Survey
LM	Lagrange Multiplier
MC	Main Carriageway
MP	Marker Post
MSA	Motorway Service Area
NB	Northbound
PFI	Private Finance Initiative
PPP	Public-Private Partnership
PTS	Professional and Technical Solutions
SB	Southbound
SES	Safety, Engineering and Standards
SRN	Strategic Road Network
UK	United Kingdom
US	United States
VAR	Vector Autoregressive
VEC	Vector Error Correction
VRS	Vehicle Restraint System
WIM	Weight-in-Motion
ZH	Zero Harm

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LIST OF PAPERS

The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research.

PAPER 1

Michalaki, P., Quddus, M, Pitfield, D. & Huetson, A, 2015. Exploring the factors affecting motorway accident severity in England using the generalised ordered logistic regression model. *Journal of Safety Research*, 55, 89-97.

http://doi.org/10.1016/j.jsr.2015.09.004

PAPER 2

Michalaki, P., Quddus, M, Pitfield, D. & Huetson, A, 2016. A time-series analysis of motorway collisions in England considering road infrastructure, socio-demographics, traffic and weather characteristics. *Journal of Transport & Health*, 3(1), 9-20.

http://doi.org/10.1016/j.jth.2015.10.005

PAPER 3

Michalaki, P., Quddus, M, Pitfield, D., Mageean, M. & Huetson, A, 2016. A sensor-based system for monitoring hard-shoulder incursions: review of technologies and selection criteria. *Proceedings of 5th International Conference on Transportation and Traffic Engineering*, Lucerne, Switzerland, July 2016.

1. BACKGROUND TO THE RESEARCH

This Thesis presents the research undertaken as part of a four-year Engineering Doctorate (EngD) programme on road workers' safety on motorways. This chapter provides an introduction to the overall subject, the background of the industrial sponsor as well as the context of the research.

1.1. THE ISSUE OF ROAD WORKERS' SAFETY

The construction industry has been one of the most hazardous occupations in the United Kingdom (UK) and worldwide. According to Eurostat, it represents one of the highest fatal as well as non-fatal accident rates *(Eurostat, 2010)*. The Health and Safety Executive (HSE) is a UK governmental organisation responsible for a wide range of activities relative to occupational safety (e.g. shaping/ reviewing regulations, enforcing the law etc.). Their statistics suggest that in the construction industry, there were 42 fatal injuries to workers in 2013/14. Although the industry accounts for only about 5% of the employees in Britain, it accounted for 31% of fatal injuries to employees and 10% of reported major/specified injuries in that year *(HSE, 2014)*.

Specifically in the roads/highways sector, it is reflected in several surveys that workers face great risk especially while operating close to live traffic. The average fatality rate for those working on the Highways England road network is one of the highest amongst all employment sectors in the UK. Between January 2006 and June 2017 there were 14 service provider workers and 2 Highways England traffic officers casualties whilst working on motorways and major A roads in England *(RoWSaF, 2017)*. While the long-term fatality trend is downwards, fatal and serious injury incidents involving workers on Highways England roads is still a cause for concern.

According to a survey of road workers conducted in 2004 by the then Highways Agency – the Executive Agency of the Department for Transport (DfT) in England which was reformed into a government-owned company, Highways England, in April 2015 – in which 400 workers participated, almost 20% stated that, in the course of their career, they had suffered some injury caused by passing vehicles, while 54% had experienced a near miss involving a vehicle. Since 1997, Highways England has been collecting data of hazards, near misses and accidents involving their road workers in the AIRSWeb database. Indicatively, only in 2010, 4,078 injuries and near misses were reported on the Strategic Road Network (SRN). From the cases where the roadworks location had been reported, 58.2% occurred within works area or safety zone which was adjacent to a live carriageway *(Transport Research Laboratory, 2011)*. STATS19 data suggest that between 2005 and 2011, out of a total of 47,870 accidents on British motorways involving an injury, 2,144 occurred when roadworks were present.

Based on the RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) notifiable incidents data, from 2006 to 2016 there were 303 serious injuries and 4,436 slight injuries of service providers staff, while there were 280 serious injuries and 3,287 slight injuries for traffic officers. It is anticipated though that there is significant under-reporting for slight injuries by service providers. Also, it is noted that the minimum lost time for a RIDDOR accident changed from more than 3 days to more than 7 days in April 2012, hence it is difficult to draw conclusions on the trends. The total cost of casualties since 2006 is £229 million, which equates to over £20 million per year.

Workers' safety is also an international issue. In the United States from 2003 to 2012, 93 highway maintenance workers were killed, representing 11.4% of all the fatalities occurred in the construction sector *(US Department of Labor, 2013)*. Fatal accident data from Netherlands also suggest that the risk of being killed during work time is higher for construction workers working on roads than for construction workers in general *(Venema et al., 2008)*.

The UK government has shown interest in increasing road workers' safety by forming relevant strategies *(e.g. Highways Agency, 2010)*. According to Highways England's Health & Safety (H&S) Five Year Plan *(2017)*, there are several at-risk populations when roadworks are in place, such as the road users, the road workers and customer operations staff. The rate of improvement in safety performance has plateaued across customer operations, which largely consists of Highways England's Traffic Officer Service, and supply chain.

In the Work Related Road Safety PRAISE International Seminar that took place in 2011, the accident rates for road workers and road construction people were presented and contrasted with the corresponding rates for all road users and Highways England roads' users. These suggest that the fatality rates per year are 1 in 1,000 and 1 in 15,000 for road workers and road construction people, while it is 1 in 16,000 and 1 in 32,000 for the road users in general and in motorways/a-roads accordingly. The Labour Force Survey (LFS), which is the largest household survey of the employment circumstances of the UK population, suggests that from 2001 to 2012, there have been on average 305 work-related non-fatal road traffic accidents to workers per year.

1.2. THE INDUSTRIAL SPONSOR

The motivation of the research finds its source in the aspiration of an infrastructure company to improve its level of safety in the workplace. Balfour Beatty is the largest business related to various infrastructure projects in the UK. It has at times received positive publicity from its satisfactory safety performance and its accident frequency rate levels. Headlines such as 'Balfour Beatty makes strides on accident rates' *(Ethical Performance, 2008)*, 'Balfour Beatty improves its safety/green performance' *(Contracts Journal, 2006)* show that H&S have been a key issue in the Company's strategy.

Balfour Beatty has four market-leading businesses: professional services, construction services, support services and infrastructure investments. The latter is represented by Balfour Beatty Investments (formerly Balfour Beatty Capital). It is an equity investor in highways and street-lighting facilities under the UK Private Finance Initiative (PFI) through its Connect Roads business brand. Connect Roads is one of the UK's largest private sector road operators, operating and maintaining 360km of trunk road network.

Connect Roads, as a subsidiary of Balfour Beatty Investments, delivers Public-Private Partnership (PPP) projects for an extended period, generally 25 to 30 years, as part of the Government's Private Finance Initiative (PFI). Specifically, Connect Roads, and in partnership with its Term Maintenance subcontractors, Designs, Builds, Finances and Operates (DBFO) highways and street lighting projects across the UK. It delivers improvements focused on journey time reliability and road worker/road user safety. It is one of the largest private sector road operators in the country undertaking five concessions and the M25 London Orbital, via its sister brand Connect Plus. The highways project list includes A30/A35, A50, Carlisle Northern Development Route (CNDR), M77/Glasgow Southern Orbital link and the M1-A1 Link Road.

The M1-A1 Link Road (Lofthouse to Bramham) was built as part of the Government's PFI (Figures 1.1, 1.2). The 30-year concession agreement (contract) was awarded to Yorkshire Link Limited in March 1996 by Highways Agency on behalf of the Secretary of State, who remains the Highway Authority for the route. The Concessionaire changed to Connect Roads in June 2004. Connect Roads operates and maintains the M1-A1 Link Road, a motorway of nearly 30km in length (89.6 km of carriageway, counting both directions and all link roads). It comprises 3, 4, 5 and 6-lane carriageways and provides strategic connections between the M1 and M62 motorways to the South of Leeds and the A1 road South of Wetherby. Along the route there are 165 structures, i.e.: 50 bridges, 7 culverts, 86 signal gantries, 15 camera aasts and 8 MS3s (motorway signals type 3).

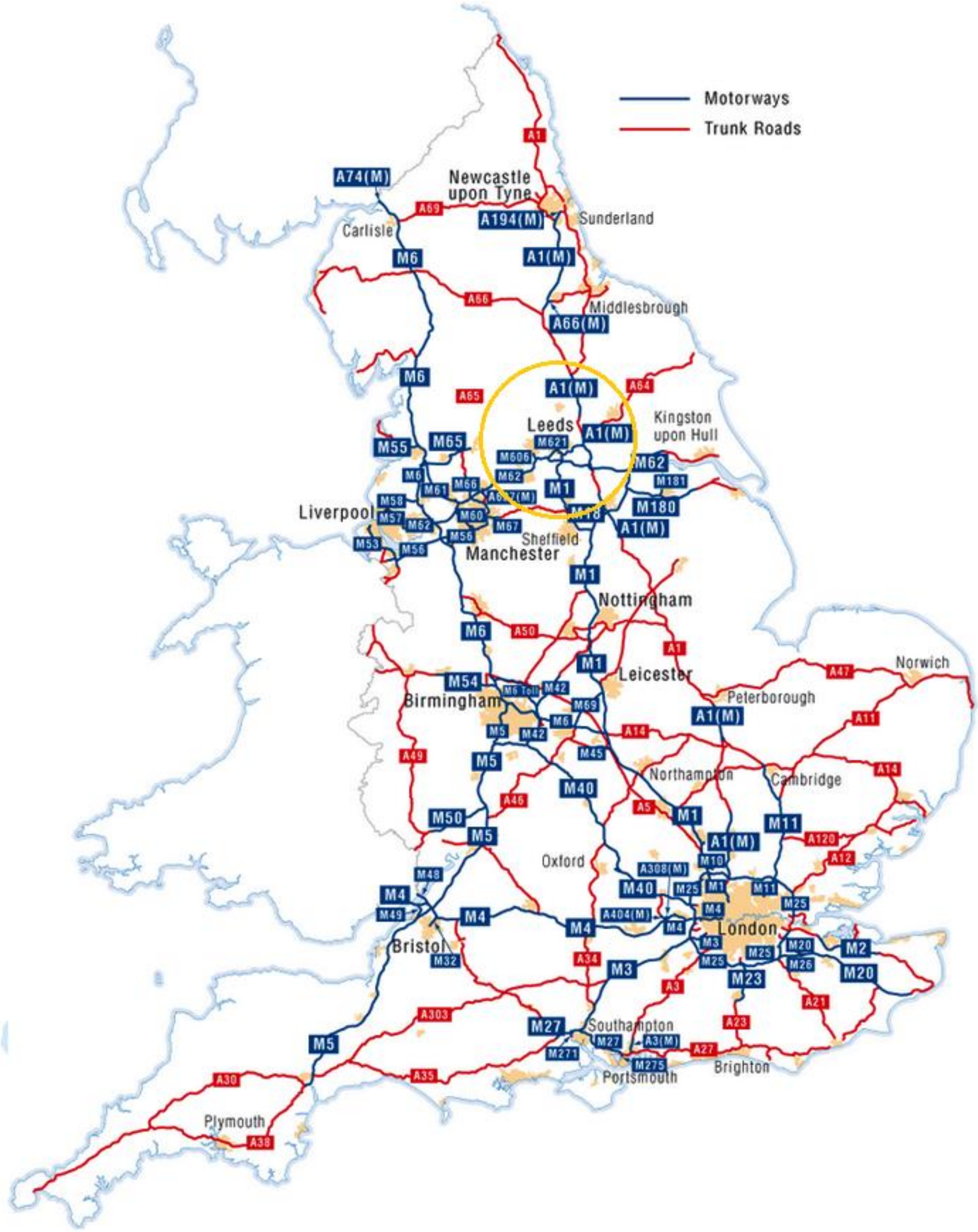


Figure 1.1 Map of motorways in England and area of study
(Source: Highways England)

In addition to the construction of the M1-A1 Link Road (between the M1 at Belle Isle – Junction 43 and the A1 at Hook Moor – Junction 43), the project included the improvement of the M62 East of Junction 28 to the Lofthouse Interchange, the M1 from Junction 42 to near Belle Isle, and the upgrading of the A1(M) from Micklefield to Bramham to motorway standard. During the 30-year concession period the Company is responsible for the operation and maintenance of the M1-A1 Link Road. The network also includes the operation and maintenance of the circulatory carriageways and associated link roads which form M1 Junction 45 and M1 Junction 46. Connect M1-A1 Limited has also employed Balfour Beatty Construction Services as its Managing Agent to carry out routine and winter service operations on the Link Road.

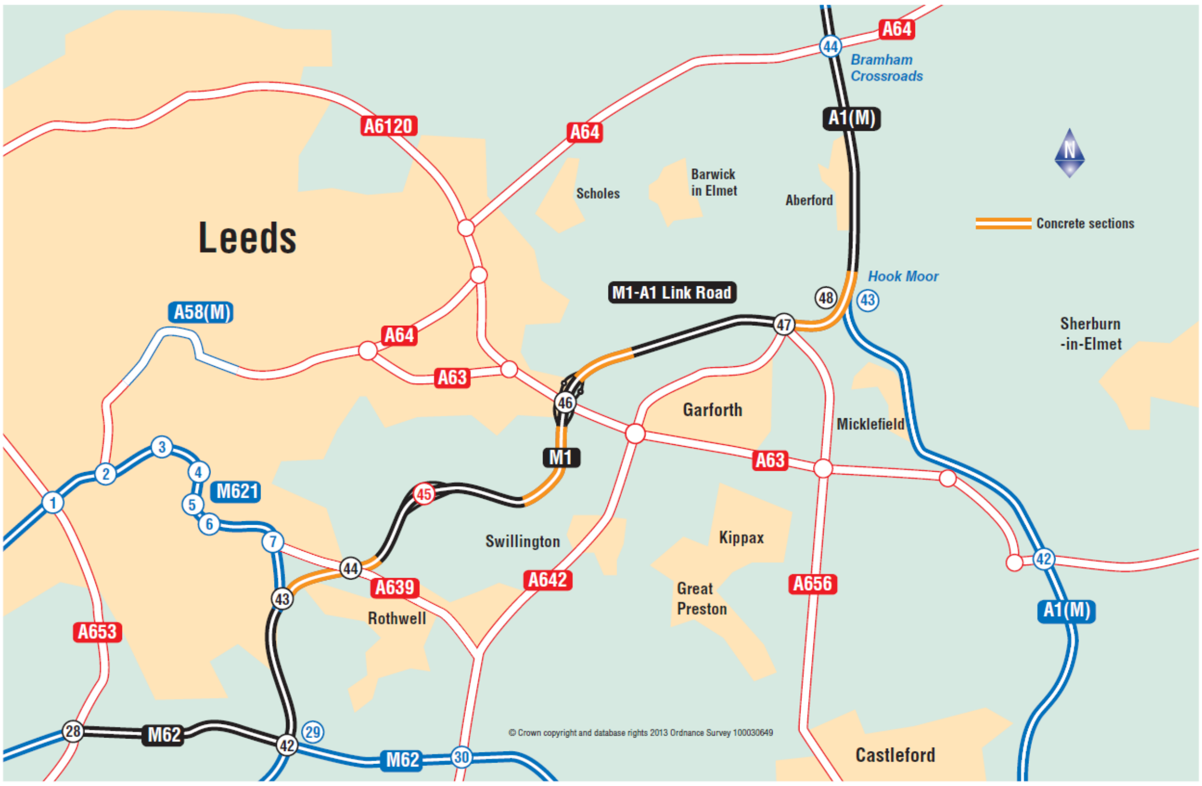


Figure 1.2 Map of Area 27 of Highways England *(Source: Highways England)*

In order to systematise H&S policies and measures, in 2008, an initiative was launched in Balfour Beatty, called *Zero Harm* (ZH). At first it had set a short-term goal to be performed until 2012. This goal included three elements:

- **Zero fatalities**
- **Zero permanently disabling injuries**
- **Zero accidents and injuries**

ZH thinking has been adopted and embedded across all Balfour Beatty's businesses. It aims to retain the trust of their customers and the people using their infrastructure. A new goal, which was set towards the end of the first agreed period, is to follow this thinking until 2020. In an online survey, that took place in 2010 regarding the personnel's opinion on whether ZH initiative has 'made a difference', the positive response showed that the contribution of this strategy has been appreciated by the employees.

Specifically, ZH means delivering on the following shared commitments:

- **Eliminating fatal risks**: All Balfour Beatty's businesses will identify fatal risks and establish ZH design, management and behavioural protocols to eliminate them.
- **Eliminating hazards**: All Balfour Beatty's businesses will identify and plan out hazards in all activities they undertake.
- **Maintaining ZH day to day**: All Balfour Beatty's businesses will establish and maintain management, monitoring, review, audit and assurance systems geared for ZH.
- **Keeping the public safe from harm**: All Balfour Beatty's businesses will manage and maintain ZH levels of separation, security, monitoring and stewardship to safeguard members of the public from exposure to our hazards.

- **Keeping all Balfour Beatty’s people healthy**: All Balfour Beatty’s businesses will conduct health checks and health risk assessments to ensure there is no long-term harm to health from working in our business.
- **Working with Balfour Beatty’s customers**: All Balfour Beatty’s businesses will enlist the support and co-operation of customers to achieve ZH.
- **Making safety personal**: All Balfour Beatty’s people will make safety a personal commitment.

The ZH Safety Initiative was introduced throughout the Balfour Beatty Group of Companies. It established forums at all levels for staff and employees to identify, examine and, where possible, eradicate H&S issues in the workplace. These forums are platforms for the workforce to raise concerns both within their immediate working environment and of construction practices in general. Directors also undertake ‘Safety Deep Dives’ and talk openly and directly with the site teams about their personal concerns for safety. They ask them to identify and recognise their own biggest risks out ‘on the job’. ZH has been considered as a way to engage better with the workplace safety problems in all concessions.

1.3. CONTEXT OF THE RESEARCH

The hard-shoulder (HS) of a motorway is normally used by the public in the event of an emergency or by emergency services as a through route to incidents. However, during operation and maintenance activities, vehicles of motorway operators often remain on the HS for short durations whilst personnel perform work under live traffic conditions and thus face various hazards. Sources of risk include:

- working directly on the HS while a motorway is in operation (partially or fully); narrow and discontinuous HS can be problematic

- access to a work site on the verge; the HS and verge being used for maintenance works such as maintaining roadside equipment and fixing potholes
- stopping for inspection
- clearing motorway debris/wreckages

The labour report of the M1-A1 Link Balfour Beatty Construction Services UK department for the financial year 2014-2015 shows how many hours were spent by the workforce on each of their tasks. In a year, the workforce spent more than 20,000 hours on the network performing tasks such as traffic management (e.g. lane closures), routine maintenance, patching, as well as drainage and gulley cleaning. Most of the time is devoted on litter picking (23% of work time), inspections (15%), grass cutting (8%) and Category 1 defects of the pavement (such as potholes), which, in opposition to patching work which is planned, need to be addressed within 24 hours (7%). Other less common activities include winter maintenance, weed control and street lighting (See ***Appendix A***).

Apart from Balfour Beatty groups, Highways England’s Traffic Safety Officers (a service that patrols motorways and responds to traffic issues including attending stopped vehicles), the Police and National Roads Telecommunications Services (who look after the communication systems, cameras and signals) have also raised their concerns about hazards on the HS, but could provide no answers to prevent them. The Police added their concern for members of the public stopping on the HS, even though advice is well-known via publicity campaigns, which is to leave the vehicle and reach a position of safety; however, they provided no conclusions on precise conditions, contributory factors for accidents.

Across several ZH workshops a common thread developed regarding the frequency of third party vehicles straying onto the HS, either where they were working or they were parked.

Incidents that had potential to be an accident are known as Safety Observations and plenty had been noticed by employees and recorded in the workplace. Each group reported several events of vehicles veering from the nearside lane of the motorway (lane 1) across the ribbed line into the HS near to where they were situated, and that they were unable to take action to avoid it. Also, observations of Highways England and other companies responsible for the operation and maintenance of British motorways show that vehicles travelling on the nearside lane accidentally often get off the carriageway and drive onto the HS. Considering that this could happen at any time an operator or emergency vehicle is stopped on the HS, it is essential to investigate under which conditions these unintentional moves could mostly occur.

Balfour Beatty's initial review concluded that the risk was significant, but needed much further investigation as it appeared that it had not been analysed before. Balfour Beatty's intention of sharing the findings could be of direct benefit to the whole Motorway Community as all members could work with more confidence by knowing the levels of risk of working on and from the HS and being able to take appropriate mitigation measures..

1.4. STRUCTURE OF THE THESIS

This thesis is outlined as follows. Chapter 2 describes the aim and objectives of the research, while in Chapter 3 the review of the literature related to motorway and road workers' safety is discussed. Chapter 4 contains the methodology followed including the four work packages in which the research was organised, which are further analysed in Chapter 5, the main part of the thesis, where the scope, method and key outcomes of each work package are presented. The closing chapter, Chapter 6, summarises the key findings and presents the contribution and impact on the existing theory and practice, the project sponsor and the wider industry, along with critical evaluation of the research.

2. OVERARCHING AIM AND OBJECTIVES

This chapter describes the aim of the EngD project along with the objectives to be completed towards to the overarching aim. The overarching aim of this research is to **explore and quantify the risk of hard-shoulder incursions for vehicles that stop on the hard-shoulder (HS).**

As private and public-owned companies (such as Highways England), responsible for highways maintenance and operation in the UK, are obliged to drive or stop on the HS to perform their activities, it is necessary for them to know what the risks on this lane of the motorway are in order to manage them. Balfour Beatty Investments want all Balfour Beatty businesses, as well as the Motorway Community stakeholders, to protect their workforce from undue risk and be able to show them the importance of H&S issues within the company's business strategy by developing a model to assess the likelihood of collision event to a stationary vehicle ion the HS. The acceptable risk levels can be agreed with the operatives and road authority and where exceeded, works could be delayed or other safety measures could be in place to manage that risk.

As the accidents that occur on the HS are only a small proportion of the total number of motorway accidents, the number is too low to reveal any patterns regarding the conditions under which the risk of having an accident is higher. Instead, a risk indicator was identified, namely the HS incursion, defined as being the ***temporary violation of the HS by vehicles that are travelling on the near-side lane of the motorway***. A risk model for road workers and the public on any motorway section may correlate the occurrences of HS incursions with conditions under which they mostly occur.

With a HS incursions risk model along with the acceptable levels of risk, highway maintenance service providers and stakeholders would be able to address their duty of care to provide a safe as possible working place for their operatives by helping towards managing the presence on the network at any given time and set of circumstances and designing solutions for difficult situations where a roadside presence cannot be avoided. Further, it would allow external factors to be monitored which may change the risk profile and allow the on-ground operations react to this. Another benefit might be cost saving by promoting a targeted response to 'public vehicular breakdowns' to be developed, as it would allow resources for recovery to be risk-orientated. It would also provide a prescriptive measure for the necessary deployment of disruptive traffic management installations in such circumstances, especially during busier periods when there is central pressure to maintain journey times.

The engagement of road user group in order for them to improve their performance and driving behaviour is also considered. The study is also looking at possible methods of attracting road user attention i.e. highlighting the immediate presence to the approaching traffic. This is complicated by general road user distraction and issues pertaining to visibility (dark/dusk, rain/spray) and practical deployment (duration, portability, ability to deploy without risk). The project can be a starting point, which can be both monitored by use of a series of recorders across the UK and developed and refined. The purpose of this would be part of the engagement with road user groups to determine the effectiveness of driver behaviour initiatives and on-going improvements.

The overarching research aim is achieved with four objectives. The first objective is to investigate the motorway accidents occurring on the HS, and the factors (infrastructure-related, traffic or other conditions) that have an impact on their severity and frequency. Then the second objective is to explore the factors affecting the occurrence of HS incursions by collecting preliminary information from manual observations. The following step is to identify and deploy a system suitable for monitoring the network for HS incursions (3rd objective). The final objective is to analyse the HS incursion occurrences and develop risk model using appropriate statistical modelling techniques. The risk model will define the probability that a HS incursion would occur at a specific location of a motorway, the underlying factors and how the risk may change over time. The research design is summarised in Table 2.1.

Table 2.1 Research design.

	Objective	Data required	Method to be applied
1	To investigate the motorway accidents occurring on the HS and the factors affecting their severity and frequency	Historic accident data on motorways Explanatory variables data (disaggregated and aggregated)	Review of motorway safety research and the potential factors for HS accidents Statistical modelling of categorical and time-series data
2	To explore the factors affecting the occurrence of HS incursions	Manual observations of HS incursions on the network	Descriptive statistics on factors affecting HS incursions
3	To identify and deploy a suitable system to monitor HS incursions	Designs of the motorway network as constructed	Review of potential HS incursion monitoring methods Review of motorway sites for the trial installation of HS incursions monitoring system
4	To analyse the HS incursion occurrences and develop risk model	HS incursions from the trial data collection system Explanatory variables data	Statistical modelling of count time-series data.

3. REVIEW OF RELATED WORK

This chapter describes the findings of the review carried out on the existing knowledge in the subject area; motorway accidents, and HS in particular. Consequently, the literature focuses on the variables that have been investigated in the past as potentially significant factors affecting road accidents, and, especially, motorway accidents.

3.1. MOTORWAY SAFETY AND ACCIDENT CONTRIBUTORY FACTORS

The review of the literature showed that no significant research has been conducted in the past into the improvement of HS safety in particular. However, there is a wealth of studies that have focused on the total number of accidents that occurred on the motorways without, though, distinguishing the ones that occurred on the HS *(Davis and Swenson, 2006; Golob, Recker and Pavlis, 2008; Lord, Washington and Ivan., 2005; Shankar, Mannering and Barfield, 1996; Wang, Quddus and Ison, 2009)*. Although the width of HS has been employed as a predictor of motorway accident frequency *(Noland and Oh, 2004)*, there is a scarcity of literature on HS accidents and consequently, there is little known about the scale of safety occurrences on the HS.

Safety in roadworks has been more extensively investigated in past research. However, work zones provide measures for risk mitigation against live traffic, for example, lane closures and speed management. Lane closures are marked by signs and cones or other traffic control devices, barriers etc. Driving behaviour normally changes through roadworks mostly by reducing speed and being more careful *(Highways Agency, 2006)*. According to Highways England's survey, this is mainly for safety reasons and also due to speed restrictions (normally 50mph). The location of accidents where temporary traffic management is in place is most frequently within the safety zone (adjacent to a live carriageway) (*Fowler et al., 2011).* More recently, alternative safety measures have been investigated, for instance using in-vehicle messages to communicate work zone events to the driver which appears to have a positive behavioural effect *(Morris, 2017)*. The physical protection in work zones and the lower average speed provide greater safety to the operatives in comparison to non-protected work on-site (for example on the HS), thus the hazards in the two situations are different. This research focuses on the accident risk where there is no temporary traffic management to mitigate the risks to the workers and the public.

Road traffic accidents occur when certain conditions are met. To gain further insight into the accident causation process, it is necessary to follow the progress of a driver from one moment to another. The driver firstly relies on his capabilities, the performance and general condition of the vehicle, as well as the road and its immediate surroundings, the other vehicles and pedestrians in the vicinity in order to try to ensure his safety. If all of these components are taken together as an element of the road traffic system, then, at any moment, the element may be in a subcritical (element at no risk of having an accident), critical (fail-to-safety condition when there is also a significant chance of having an accident) or supercritical (fail-to-accident condition) state, which can be transformed while driving from one to another. A series of factors can lead to an accident, such as a sudden unanticipated serious failure, prolonged or regularly repeated failures, interactions of two or more elements that are in the critical state, interaction of two or more components in critical conditions within a given element or any one or more of the above *(Asalor, 1984)*.

Identifying causes of accidents and possible individual and external factors that increase the accident risk for the driver improve the development of educational and technological countermeasures related to traffic safety *(Häkkänen and Summala, 2001)*. A road traffic system can be considered to consist of two essential predominantly engineering subsystems: the road and its environment on the one hand, and the vehicle (including its contents but excluding the driver) on the other; and two predominantly human subsystems: the driver and the pedestrian, which are interacting whenever the system is functioning. A road traffic accident is a type of failure of the system that results in abnormal wear, tear or damage to life and property. It is assumed that every road traffic accident is traceable to a certain minimum degree of system malfunction. The reverse – namely that every single system malfunction that is equal to or in excess of the minimum value always results in an accident – is not true *(Asalor, 1984)*.

Literature suggests that road accidents are related to various factors, engineering (related to the infrastructure characteristics of the road, the traffic or the environment conditions at the time of the accident) and human related. In the following sections, each of these categories is discussed in more detail.

3.1.1. Engineering factors

- **Road design**

The relationships between road traffic accidents and highway geometric design variables, such as horizontal curvature, vertical grade, lane width, and shoulder width have been empirically investigated through statistical models in numerous studies *(e.g. Okamoto and Koshi, 1989; Miaou, 1994; Haynes et al., 2007; Kononov, Bailey and Allery, 2008)*. For a fixed curvature degree, Zegeer suggested that as the length of curve increases, the accident rate increases *(Zegeer et al. 1990)*. It has also been suggested that as length of grade increases to a point that can slow a Heavy Goods Vehicle (HGV) to a significantly slower speed than the speed of the ordinary traffic, the accident rate increases *(Roy Jorgensen Associates, Inc. 1978).*

- **Traffic conditions**

Regarding traffic statistics, speed appears to be important for both the severity and frequency of accidents and is included in several alternative forms, for instance average speed, speed limit and speed variation *(Elvik,, Christensen and Amundsen, 2004; Aarts and van Schagen, 2006).* Several factors determinate speed behaviour and intentions. Contextual endogenous (aim of trip or emotional state of driver) and exogenous factors (weather and infrastructure conditions) have an effect on drivers' speed behaviour *(Letirand and Delhomme, 2005).* Also, drivers have appeared to be concerned about other road users in their choice of speed and a driver who perceives others to drive at excessive speeds is more likely to drive faster *(Haglund and Åberg, 2000).* Traffic is also expressed using a range of variables, such as traffic flow, traffic density and congestion *(Golob, Recker and Alvarez, 2003; Golob, Recker and Alvarez, 2004; Wang, Quddus and Ison, 2013).*

- **Environmental conditions**

Inclement prevailing weather conditions appear to be quite significant for road accidents in various aspects, namely precipitation, wind and fog. Rainfall is suggested to affect drivers in different ways across different geographic areas and times of the day *(Brijs., Karlis and Wets, 2008).* Previous research has also shown that the effect of extreme weather is much greater than purely seasonal factors.

Road vehicles in strong winds can experience a variety of problems depending upon the vehicle type, shape and the wind dynamic. High-sided vehicles are prone to being completely blown over in high cross winds, whilst smaller, lighter vehicles such as vans or cars can be forced to deviate significantly from their path at gusty locations. *(Edwards, 1994).* Unlike other weather hazards, such as rain (where there is a decrease in accident severity) and fog (which results in an increase in the severity of an accident), there appears to be inconclusive evidence regarding the effect of high winds on accident severity *(Edwards, 1994).*

In Great Britain (GB), it has been supported that the problems to traffic caused by wind are exacerbated because many of the main routes (especially motorways) run Northwest-Southeast, that is up and down the country, due, essentially, to the shape and orientation of mainland Britain *(Edwards, 1994)* and as a result, the general traffic movements are at right angles to the prevailing south-westerly winds from the Atlantic, although this situation is complicated by turbulence and vehicle speed.

3.1.2. Human factors

Human factors also play a very important role in road accidents. In general, different groups of drivers have a different risk of being involved in an accident. HGV drivers have been proved to be in the high risk group *(Charbotel, Martin and Chiron, 2010).* In the UK, fatal road accidents per 100 million vehicle kilometres involving HGVs are almost double of those involving cars *(Department of Environment, Transport and the Regions, 1998).* Identifying risky drivers could facilitate more effective traffic safety work and allow measures to be tailored towards a specific driver group.

Driver age too appears to be important as younger drivers are most commonly involved in collisions whether from inexperience, in-vehicle distraction or other reasons *(e.g. NHTSA , 2008; Hassan and Abdel-Aty, 2013).* Gender has also been found to be important as male drivers generally are more often involved in collisions than females. It is further recognised that they are more prone to driving violations, and risky driving *(e.g. Evans, 1991;*

Constantinou et al., 2011). Conversely, alcohol impairment is a common causal factor of collisions, especially the ones involving injury, amongst men and women *(e.g. Holubowycz, Kloeden and McLean, 1994).*

Driver fatigue appears to be one of the most often reported factors in road accidents, especially with HGV drivers *(e.g. Nordbakke and Sagberg, 2007; Zhang and Chan 2014).* Several previous studies have reported that they face fatigue-related problems while driving *(Häkkänen and Summala, 2000; Zhang and Chan, 2014)* and the drivers themselves recognise it *(Häkkänen & Summala, 2001).* According to *Karrer and Roetting (2007)* falling asleep at the wheel is one of the leading causes of fatal accidents and injuries, accounting for up to 15–20% of all traffic accidents in developed countries. However, it is often overlooked in police reports, as some drivers are deceased in the accidents, while surviving ones may be unwilling to admit that they were asleep behind the wheel *(Corfitsen, 1999).*

Nordbakke and Sagberg's study *(2007)* showed that most drivers experience various symptoms of sleepiness, such as difficulty keeping their eyes open, before they fall asleep while driving. However, those symptoms are not taken seriously enough; this may be due to an underestimation of the relation between the various physiological and behavioural signals. Even though drivers often fight the symptoms of sleepiness even before the trip, they sometimes overestimate their own capability. In spite of the drivers' knowledge of the risk, most drivers continue to drive even when recognising sleepiness while driving. The justification for this is most commonly related to the distance to be driven – total or remaining *(Nordbakke & Sagberg, 2007).*

On British motorways, drivers have been encouraged to take a break when feeling tired with the establishment of safety signs in the 1990's by the then Highways Agency (now Highways England). These permanent messages read 'Tiredness can kill – Take a break' and are normally placed ahead of the Motorway Service Areas (MSAs). Their aim is to remind drivers to stop when necessary in safe areas and not in inappropriate places such as the HS *(Horne and Reyner, 2001)*. The MSAs are government-approved facilities in the UK designed to provide a safe exit and rest areas for drivers using the motorway network *(Motorway Services Online, 2015)*.

Table 3.1 Summary of factors affecting motorway accidents.

Motorway accident factors		
Engineering	Road design	• Horizontal curvature • Vertical grade • Lane width (and HS width)
	Traffic conditions	• Speed (average, variation, limit) • Traffic flow • Traffic density • Congestion
	Environmental conditions	• Precipitation • Wind • Visibility
Human		• User group (private vehicle/ HGV) • Age group & gender • Fatigue • Impairment

3.2. POTENTIAL SYSTEMS FOR MONITORING HS INCURSIONS

A HS incursion is defined as the temporary violation of the HS rib-line by ordinary traffic which is travelling on the near-side lane of the motorway. Data of HS incursions need to be obtained on real-world motorway operations. In order to develop a trial system for data collection, traffic counting/vehicle detection methods are considered.

The HS incursion data may be collected using a system across the motorway based on the existing infrastructure. Connect Roads, as the responsible company for the operation and maintenance of the M1A1 Link Road, has in operation 15 closed-circuit television (CCTV) cameras installed in 30 kilometres for surveillance purposes. With the help of CCTV cameras, videos recorded at any time on the motorway can be watched in order to notice HS incursion events at specific sections, which is, though, time consuming even at a high speed. The major advantages of this method would be the zero installation time and cost as it is an already existing system. However, the sites where the cameras are installed are predetermined and, as a result, there is no flexibility in choosing alternative sections of the motorway, if necessary. Lastly, the cameras good visibility to recognise the HS incursions is not guaranteed due to low visibility (e.g. night-time or sun glare) (Figures 3.1-3.3). Even if the occurrence of an HS incursion is visible, information such as the width and length of the HS incursion would still be hard to be recognised.

The installation of new technology is then considered, as the already installed CCTV cameras do not seem to be adequate for the purpose of the research. The new cameras should be able to provide good visibility in order to capture image in total or partial darkness at all times. An example of an alternative camera type would be the ‘Night Hawk CCTV camera’ *(Gizmag, 2003)* which is capable of capturing images in total darkness with built-in Light-Emitting Diode (LED) illuminators. Other options might be the Pro Sony electronics pack (0.01 lux) which also performs very well in low-light or infra-red light conditions *(CCTV42, 2013)* or the B8-series Premium body day/night camera *(CCTV42, 2013)* which works throughout the whole day and at the same time allows high levels of detail to be captured even at long distance with the help of powerful lens while it is easy to install and set up. The costs and the associated complexity in analysing the images need to be carefully investigated while deciding on this technology.

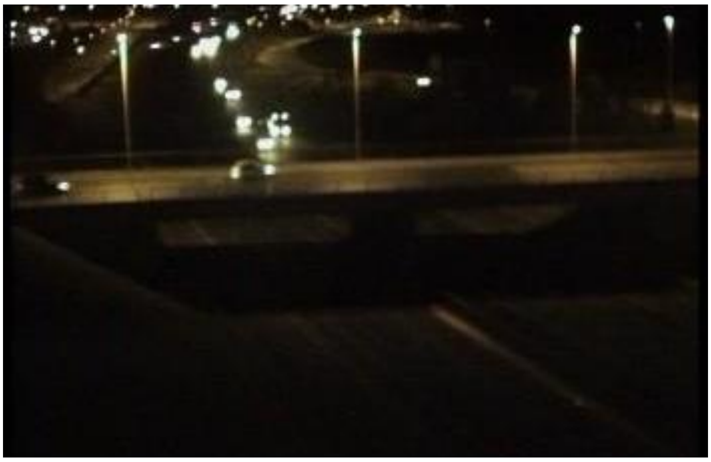


Figure 3.1 M1 Northbound Motorway, Junction 46, Leeds – visibility problems at night-time

Figure 3.2 A1(M) Northbound Motorway, Junction 42, A63 – visibility problems due to sun glare

Figure 3.3 M1 Northbound Motorway, Junction 45 – visibility problems due to sun glare *(Source: www.motorwaycameras.co.uk)*

There are two main categories of equipment for collecting traffic data in terms of the way of placement: intrusive and non-intrusive devices. Intrusive, which are the traditional ones, devices are those that involve placement of the sensor technology on top of or into the lane of traffic being monitored. They represent the most common devices used today including inductive loops, piezo-electric sensors and pneumatic rubber road tubes. In opposition to the above, non-intrusive counting devices do not interfere with traffic flow either during the installation or the operation phase *(Skszek, 2001)*. The intrusive devices are, generally, exacting in terms of traffic management measures at the time of installation on the motorway. Based on current knowledge, alternative solutions, such as GPS-based data, are not expected to be capable of providing accurate information for the purpose of this research, for instance vehicle location, thus are not further explored in this review.

3.2.1. Intrusive methods

3.2.1.1. Bending plate

This technology is most frequently used for collecting weight-in-motion (WIM) data. The device typically consists of a weigh pad attached to a metal frame installed into the travel lane. A vehicle passes over the metal frame causing it to slightly bend. Strain gauge weighing elements measure the strain on the metal plate induced by the vehicle passing over it. This yields a weight based on wheel/axle loads on each of two scales installed in a lane. The device is also used to obtain classification and speed data. *(Skszek, 2001; Leduc, 2008)*.

Figure 3.4 Bending plate WIM system *(Source: International Road Dynamics, Inc.)*

This equipment is labour-intensive to install. It requires fixing the device to the roadway, so intrusion in the flow of traffic is necessary. The bending plate appears to be, in some cases, suitable to suit all lane widths, and can be installed in asphalt, Portland cement or concrete pavements. WIM technologies of International Road Dynamics Inc. may be integrated with other traffic data systems, to provide advanced HGV weighing, traffic data, traffic safety, toll collection, and security and access control systems *(Traffic Technology Today, 2009)*.

3.2.1.2. Pneumatic road tube

A pneumatic road tube is a hollow rubber tube placed across the roadway that is used to detect vehicles by the change in air pressure generated when a vehicle tire passes over the tube. A device attached to the road tubes is placed at the roadside to record the change in pressure as a vehicle axle. Axle counts can be converted to count, speed, and/or classification depending on how the road tube configuration is structured *(Skszek, 2001)*. The main drawback of this technology is that it has limited lane coverage and its efficiency is subject to weather, temperature and traffic conditions. This system may also not be efficient in measuring low speed flows *(Leduc, 2008).*

Figure 3.5 Pneumatic tube *(Source: Rodrigue, 2011)*

The pneumatic road tube is installed across the roadway and is attached to a counting device that is placed along the roadside. The placement takes up to an hour, but requires some intrusion into the flow of traffic *(Skszek., 2001; Smith and McIntyre, 2002)*. It is easy, quick and requires minimum technical expertise *(Skszek., 2001)*. In addition, the purchasing cost is relatively inexpensive *(Rodrigue, Notteboom and Shaw, 2013)*.

3.2.1.3. Piezoelectric Sensor

Piezo-electric sensors are mounted in a groove that is cut into the roadway surface within the traffic lane. The sensors gather data by converting mechanical energy into electrical energy. Mechanical deformation of the piezoelectric material modifies the surface charge density of the material so that a potential difference appears between the electrodes. The amplitude and frequency of the signal is directly proportional to the degree of deformation. This system can be used to detect and record vehicle count, weight and speed *(Skszek, 2001; Leduc 2008)*.

Figure 3.6 Piezo-electric sensor *(Source: International Road Dynamics, Inc.)*

Piezo-electric sensors can be placed across the road surface or imbedded in the roadway. Imbedding the sensor requires cutting into the asphalt or concrete surface. The counting device is placed at the roadside. Installation can take less than an hour if the sensors are on top of the road surface or can take up to two days if placed into the roadway *(Skszek, 2001)*.

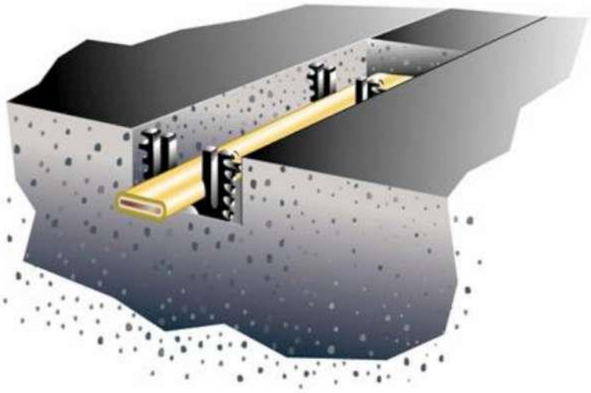


Figure 3.7 Piezo-electric sensor sketch *(Source: Measurement Specialties, Inc.)*

The sensor above (Roadtrax BL Traffic Sensor) is designed for permanent or temporary installation into or onto the road surface for the collection of traffic data. The unique construction of the sensor allows direct installation into the road in a flexible format so that it can conform to the profile of the road. The flat construction of the sensor gives an inherent rejection of road noise due to road bending, adjacent lanes, and bow waves of approaching vehicles. The small cut in the road minimizes the damage done to the road, speeds up the installation and reduces the amount of grout used for the installation.

3.2.1.4. Inductive (or Magnetic) Loop

An inductive loop is a wire embedded into or under the roadway in roughly a square configuration. The loop utilizes the principle that a magnetic field introduced near an electrical conductor causes an electrical current to be induced. In the case of traffic monitoring, a large metal vehicle acts as the magnetic field and the inductive loop as the electrical conductor. The information is transmitted to a counting device placed on the side of the road *(TransCore, 2001).*

It has a generally short life expectancy because it can be damaged by heavy vehicles, but is not affected by bad weather conditions. However, the implementation and maintenance costs can be high Inductive loop installation can take up to two days and will require lane closures. Clearview Intelligence, the company responsible for the traffic data collection on behalf of Connect Roads, uses inductive loops for this purpose. However, since they are installed only closed to junctions, they are not able to cover all the different locations needed.

An example of an inductive loop product is the technology that Eco-Counter, Inc has developed is an inductive loop inserted in the road in a depth of 2 to 5 cm and is totally invisible. Each time a car goes over the loop, the system detects the wheels electromagnetic signature and registers a count. The loop is 2.5 m wide and it is possible to join up to 4 loops together. It has energy autonomy up to 1 year using a battery. The system can be used for permanent or semi-permanent counting. The sensor can also be used for temporary counting.

Figure 3.8 Inductive loop installed in the road *(Source: Eco Counter, Inc.)*

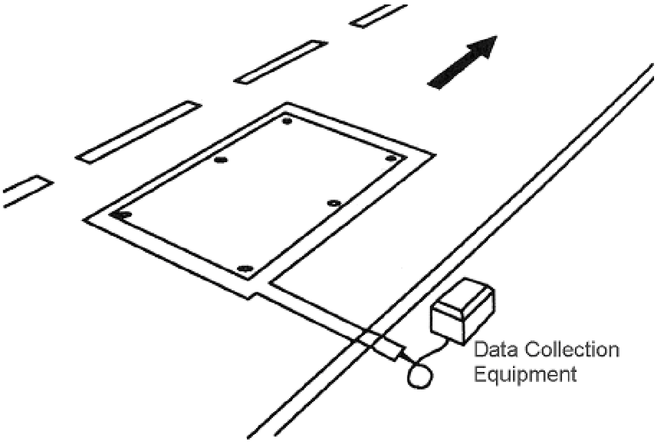


Figure 3.9 Inductive loop sketch *(Source: Traffic Detector Handbook, 2006)*

3.2.2. Non-intrusive methods

3.2.2.1. Manual Observation

Manual observation involves detection of vehicles with the human eye and hand recording count and/or classification information. Hand-held devices are available for on-site recording of information gathered by one or more individuals observing traffic *(Skszek, 2001)*. Most applications of manual counts require small samples of data at any given location. This method is sometimes used when the effort and expense of automated equipment are not justified, or when automatic equipment is not available, and typically for periods of less than a day. Normal intervals for a manual count are 5, 10, or 15 minutes *(Smith and McIntyre, 2002).* There are certain requirements on the size of the team and the duration of data collection for the avoidance of fatigue *(Robertson 1994; Smith and McIntyre, 2002).*

Observers must be positioned where they have a clear view of the traffic. Observers should be positioned away from the edge of the roadway. If observers are positioned above ground level and clear of obstructions they usually have the best vantage point. Visual contact must be maintained if there are multiple observers at a site. In the case of HS incursions, since the counting would take place on the motorway, the selection of a location for the data collection team would be challenging in terms of safety. In addition, this method would not be efficient when visibility is reduced.

3.2.2.2. Infrared

Passive infrared devices detect the presence of vehicles by measuring the infrared energy radiating from the detection zone. The infrared energy naturally emanating from the road surface is compared to the energy radiating when a vehicle is present. Since the roadway may generate either more or less radiation than a vehicle, the contrast in heat energy is detected. The possibility of interference with other devices is minimized because the technology is completely passive. Passive infrared detectors are typically mounted directly over the lane of traffic on a gantry, overpass or bridge or alternatively on a pole at the roadside. Active infrared devices emit a laser beam at the road surface and measure the time for the reflected signal to return to the device. When a vehicle moves into the path of the laser beam the time it takes for the signal to return is reduced. The reduction in time indicates the presence of a vehicle. The mounting position for active infrared detectors is more variable; it can over the lane or at the roadside. Both active and passive infrared devices can be used to record count, speed, and classification data. The main drawbacks are the performance during bad weather, and limited lane coverage *(Skszek, 2001; Leduc 2008).*

3.2.2.3. Passive Magnetic

Passive magnetic devices detect the disruption in the earth's natural magnetic field caused by the movement of a vehicle through the detection area. To detect this change, the device must be relatively close to the vehicles. This limits most applications to installation under or on top of the pavement, although some testing has been done with side fire devices in locations where they can be mounted within a few feet of the roadway. Magnetic sensors can be used to collect count, speed, and classification data; however, in operating conditions the sensors have difficulty differentiating between closely spaced vehicles *(Skszek, 2001; Leduc, 2008).*

3.2.2.4. Microwave – Doppler/Radar

This technology can detect moving vehicles and speed. It records vehicle counts, speed and simple vehicle classification and is not affected by weather conditions. The detector registers a change in the frequency of waves occurring when the microwave source and the vehicle are in motion relative to one another. According to the Doppler principle, when a moving object reflects the radar beam emitted from the detector, the frequency of the reflected wave is changed proportionally to the speed of the reflecting object. This allows the device to detect moving vehicles and determine their speed *(Skszek, 2001).*

Radar (RAdio Detection And Ranging) is capable of detecting distant objects and determining their position and speed of movement. With vehicle detection, a device directs high frequency radio waves at the roadway to determine the time delay of the return signal, thereby calculating the distance to the detected vehicle. Radar devices are capable of sensing the presence of stationary vehicles. They are insensitive to weather and provide day and night operation. The device is placed in a side-fire mount off the shoulder of the roadway. This technology is capable of recording count, speed, and classification data *(Skszek, 2001)*.

3.2.2.5. Ultrasonic and Passive Acoustic

These devices emit sound waves to detect vehicles by measuring the time for the signal to return to the device. The ultrasonic sensors are placed over the lane and can be affected by temperature or bad weather. The passive acoustic devices are placed alongside the road and can collect vehicle counts, speed and classification data. They can also be affected by bad weather conditions (e.g. low temperatures, snow) *(Leduc, 2008)*. Passive acoustic devices detect the sound from a vehicle passing through the detection zone and it then compares the sound to a set of sonic signatures pre-programmed to identify various classes of vehicles. The primary source of sound is the noise generated by the contact between the tyre and road surface. These devices are best used in a side on position, pointed at the tyre track in a lane of traffic to collect count, speed, and classification data *(Skszek, 2001)*.

3.2.2.6. Video Image Processing

Video image processing devices use a microprocessor to analyse the video image input from a camera. Trip line techniques monitor specific zones on the roadway to detect the presence of a vehicle. Video tracking techniques employ algorithms to identify and track vehicles as they pass through the field of view. Optimal mounting position for video image detectors is directly over the lane(s) to be monitored with an unobstructed view of traffic. Side mounting is feasible but large vehicles may obstruct detection zones. The mounting height is related to the desired lane coverage, usually 35 to 60 feet above the roadway. Video detection devices are capable of recording count, speed, and classification data. The system can be sensitive though to meteorological conditions *(Skszek, 2001; Leduc, 2008)*. Video image processing has developed significantly as a technology for vehicle and incident detection in the last few years; however, at the time that this research was initiated, other technologies appeared more suitable.

Table 3.2 Technology characteristics for automatic HS incursions data collection.

Technology		Advantages	Disadvantages
Intrusive	Inductive loop	Well established technology. Insensitive to weather. Low cost.	Does not provide information on the exact position of the vehicle.
	Pneumatic road tube	Low acquisition cost. Easy to install.	May be displaced resulting in loss of data. Snow can damage road tubes. If installed in a perpendicular direction to the traffic, the severity of HS incursion cannot be measured. A parallel installation is examined as an alternative.
	Bending plate	Low acquisition cost.	Requires working within the traffic lane and is time consuming.
	Piezo-electric sensor	It counts weight and speed.	Does not provide information on the exact position of the vehicle. Requires working within the traffic lane and is time consuming. If placed on road surface, may be displaced resulting in loss of data.
Non-intrusive	Magnetic	Insensitive to weather. Ease of deployment.	Difficulty in discriminating longitudinal separation between closely spaced vehicles.
	Infrared	Accurate measurement of vehicle position and speed. Multiple lane operation available.	Operation may be affected by low visibility. Installation and maintenance require lane closure. Requires regular maintenance. High cost.
	Radar	Insensitive to weather. Can potentially collects all the data required.	High cost.
	Ultrasonic	Low cost.	It can be affected by environmental conditions.
	Video image processing	Easy to add and modify detection zones.	Performance affected by inclement weather. Reliable night-time signal actuation requires street lighting.

For this research, a trial system for monitoring HS incursions is considered. In this case, non-intrusive solutions would clearly be preferable, as they would be less disruptive to the traffic and the infrastructure. Weather conditions are potentially important for HS incursions and the risk may be higher when visibility is low, and hence the sensors selected should be able to perform well in periods of inclement weather. A more detailed discussion of the factors that were taken into consideration when selecting the most suitable technology is provided in the following chapter.

Overall, the research questions can be summarised as:

- What are the underlying factors of motorway HS accidents?
- What are the underlying factors of HS incursions?
- Is it possible to design a tool capable of monitoring risk events on the HS?
- What is the probability that a HS incursion would occur at a specific location of a motorway?

4. RESEARCH METHODOLOGY

The methodological steps followed to achieve each of the research objectives through four work packages, in which a range of research methods is employed, are described in this section. The EngD project focuses on the exploration and quantification of the risk of HS incursions. A HS incursion is defined as the ***temporary violation of the HS by vehicles that are travelling on the near-side lane of the motorway*** (e.g. Figure 4.1). Figure 4.2 illustrates a typical incursion, where L represents the maximum length of the incursion and D the maximum width. However, it is anticipated that the trajectory of a vehicle over the HS may not be as clearly defined.

The definition of risk is broadly accepted as two-dimensional, based on the likelihood of an event (HS incursion) occurring and the impact of that event once it occurs. The first relates to *uncertainty,* since a risk is something which has not yet happened and which may or may not occur and is defined either as frequency or probability. The latter is about what would happen were the risk to occur, since risks are defined in terms of their *effect.* The impact (from negligible to extreme) depends on the injuries/casualties caused in the case of the event. In this project, the impact of incursions is unknown, thus the risk is defined only based on ***likelihood***.

Figure 4.1 HS incursion of a HGV on the motorway (slight/serious)

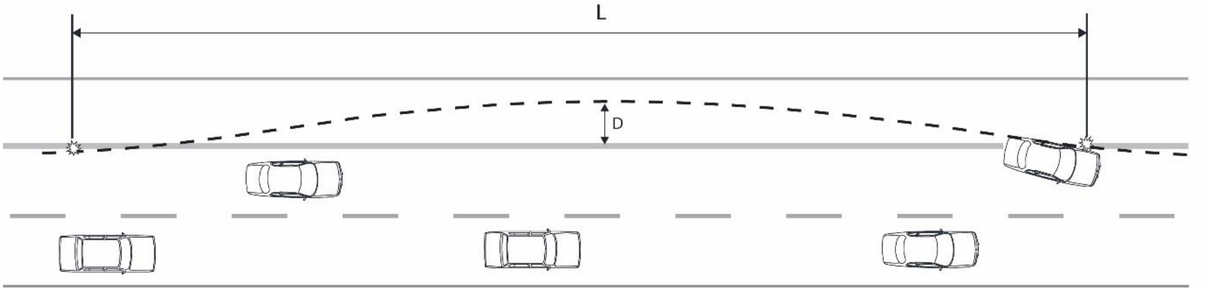


Figure 4.2 Definition of a HS incursion

4.1. 1ST RESEARCH OBJECTIVE: INVESTIGATION OF HS ACCIDENTS

The first research objective is to investigate the motorway accidents occurring on the HS in terms of the factors that have an effect on their frequency and severity. According to *Heinrich (1959)* and the safety triangle theory, the ratio between fatal accidents, accidents, injuries and minor incidents is relatively constant over time and across work sectors.

According to Heinrich’s theory, the fatal accident rate is linked to the serious accident rate and also linked to the near miss rate with the ratio of 1:29:300. This theory has been widely adopted in principle, even though the ratios have been challenged. For instance, the HSE has suggested a ratio of 1:7:189 for major or over-three-day lost time injuries, minor injuries and non-injury accidents (Figure 4.3). Figure 4.4 shows how the safety triangle theory is applied on HS incursions.

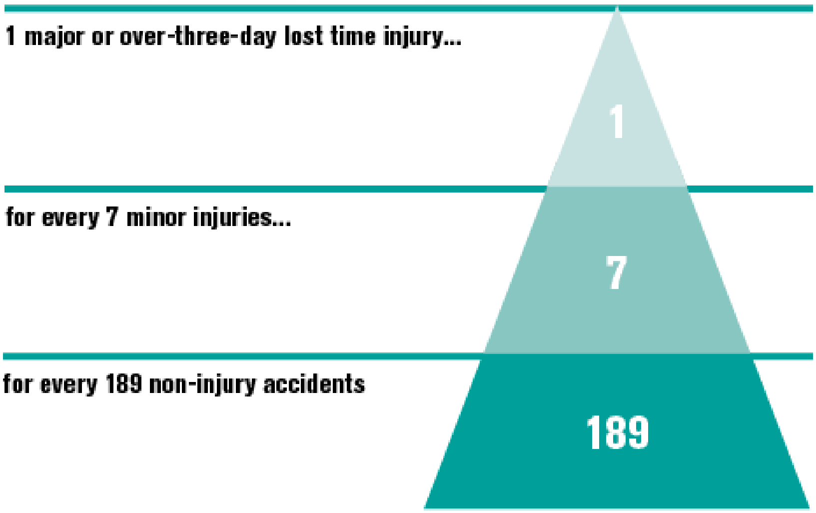


Figure 4.3 HSE's safety triangle

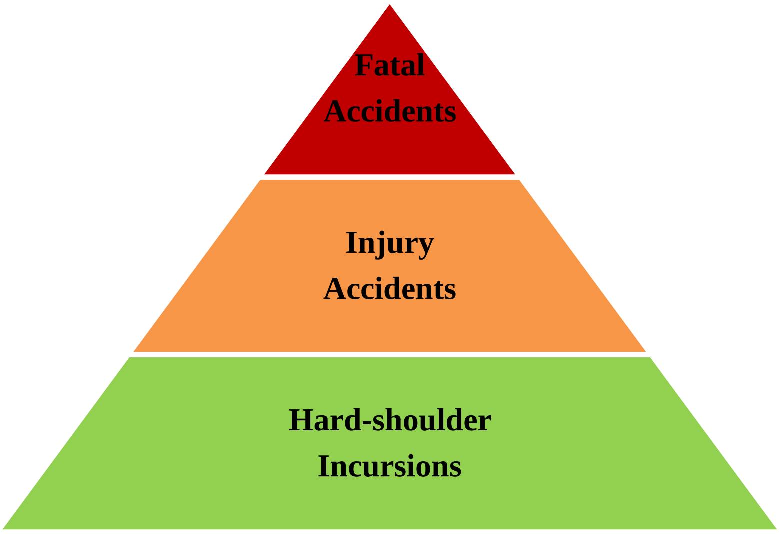


Figure 4.4 The safety triangle for HS incursions

Even though the conclusions may not be drawn for causality relationship between fatal accidents, injury accidents and HS incursions, it is assumed that an investigation of the factors contributing to HS accidents would also provide knowledge on the potential factors that may contribute to HS incursions. An in-depth literature review is conducted and no significant work was discovered in the field of HS accidents, even though previous research is rich on motorway safety. The review of past studies does, however, provide a good level of knowledge in terms of the approaches used to understand motorway safety. This includes the statistical methods that have been utilised in order to model either the severity or the likelihood of motorway accidents, as well as the external factors that contribute to these.

The frequency and severity of the accidents occurring on motorways, and in particular on the HS, are investigated using suitable analytical techniques, as discussed in ***Paper 1*** and ***2***. Using GB as the study area of research, data from STATS19, the police recordings of all highway injury accidents in GB, are collected from 1985 to 2011. The accident database, which initially includes all roadway types, offers various information on the accident itself (e.g. time, location, class of the road, ambient conditions), the vehicles involved (e.g. vehicle type, movement, location) as well as the casualties caused (gender, age, type of casualty, severity).

The purpose of this research package is to examine the HS and MC accidents separately to justify if they present significant differences in their occurrence in terms of frequency and impact. This is achieved by a quantitative approach and, more specifically statistical analysis, using suitable models on the STATS19 data. The models used in this work package are discussed in detail in ***Paper 1*** and ***Paper 2***. The outcome of this package will be the factors affecting motorway accidents (or HS and MC accidents), which, based on Heinrich's safety triangle assumption, will provide feedback on what information needs to be collected in the future research steps to investigate HS incursions in particular.

4.2. 2ND RESEARCH OBJECTIVE: EXPLORATION OF THE FACTORS AFFECTING THE OCCURRENCE OF HS INCURSIONS

The second research objective is to explore the factors affecting the occurrence of HS incursions using preliminary information. To achieve this, a survey via field observation/experiment is conducted, in which HS incursions are observed manually on the motorway. This is to collect data related to the frequency of HS incursions as well as the conditions under which these are happening. The approach of this survey is to record incidents from moving observers (i.e. probe vehicles) that drive on the network.

Observation, as a research method, presents several advantages and drawbacks. The advantages of observation are the real-time data collection, in opposition to relying on people's willingness to provide information in surveys, and also the directness, which eliminates the subjectivity when people are stating their behaviour. On the opposite side, disadvantages include the possibility of the observation being susceptible to observer bias, as well as the Hawthorne effect which refers to people usually performing better when they know they are being observed. Finally, observation does not enhance understanding of the reasoning behind people's behaviour. Investigating the positive characteristics in the frame of HS incursions data collection, it is noted that all of them are applicable. On the contrary, not all disadvantages would affect this survey. Observer bias is not applicable, as this would occur if the observers could allow the purpose of the study to influence their observations and neither Hawthorne effect is, as the observers are not aware of themselves being observed.

The observers are Balfour Beatty Construction Services' employees who normally spend significant time driving on motorways across the UK. Balfour Beatty Construction Services is the company division responsible for the daily maintenance of the network. More specifically, these employees are engaged in activities such as:

- patrolling, monitoring and reporting on the network condition

- undertaking routine maintenance activities
- making safe defects to the highway infrastructure

The drivers are always accompanied in the vehicle by a co-driver. This allows them to make observations and keep notes while still driving safely. The number of HS incursions can provide information about the frequency of occurrences while the severity of the incursion is distinguished as slight and serious according to the width of the violation over the rib-line. Photos of a slight and a serious incursion are displayed on the survey form, so that the participants have a clear comparison of both occasions. Other variables collected from this survey which can be correlated with the frequency and severity of incursions are related to the time of the day (daytime/night-time), the level of visibility (good/poor) as well as the pavement condition (dry/wet). The survey information required is kept brief and simple, so that the drivers are encouraged to fill it in. The outcome of this research package is further feedback on the information an automatic HS incursions monitoring system needs to collect.

4.3. 3RD RESEARCH OBJECTIVE: DEPLOYMENT OF A HS INCURSIONS DATA COLLECTION SYSTEM

The third research objective is to identify and deploy a system suitable for monitoring HS incursions. To estimate the risk of incursions, the incursion frequency over a specified time period at a specific location needs to be monitored. For this purpose, further literature review is conducted to investigate automatic systems for vehicle detection and/or traffic counting ***(§3.2)***. As there is already technology installed on the M1-A1 Link Road, the potential use of the existing devices will also be considered.

The data for HS incursions will be collected using a ‘black box’ tool measuring across the motorway. One way this could be realised is with the help of the CCTV system which is already installed on the network for surveillance reasons. However, manually reviewing the videos from the CCTV cameras of the motorways can be a very time-consuming process, and also manual observations are not an effective option for a long data collection period. Thus, it is aimed to develop an automated way to collect incursion data in order for them to be more accurate for 24/7 monitoring. The system requirements are the following: detecting, measuring, identifying, recording and storing data.

- **Detecting**

The system must detect the violations of the nearside rib-line, which is the line separating the HS from its adjacent lane. These violations are caused by vehicles that are not positioned in the middle of the lane and cross the rib-line. Since we are only interested in HS violations – and not lane-changing – these are considered to be unintentional. The only exception to this is the confusion that might prevail on Smart Motorways. On these roads, the HS either constantly, or when necessary, is used as a running lane to reduce congestion; however, members of public often use this lane by mistake when it is closed. However, this study is conducted on a standard motorway (3 lanes + HS).

- **Measuring**

While detecting HS incursions, the system must also measure additional characteristics relative to the incursion at an accurate level, such as the trajectory or the area that a vehicle covers on the HS, and the time of detection.

- **Identifying**

The incursions must be corresponded to the ‘identity’ of the vehicle, i.e. the classification of the vehicle and its speed.

- **Recording and storing**

The system must also be capable of recording and storing all the above information so the data is available for further manipulation.

The speed of the vehicle, according to the technology used, might be directly collected or estimated. The classification of the vehicle can be either in two categories (e.g. car or HGV) or in multiple categories (e.g. car, van, bus, HGV, transporter or caravan). Some of the methods for vehicle classification are based on the number of axles and space between them, the length of the vehicle, the body or trailer type, the vehicle weight or the engine/fuel type.

The exact day and time of an incursion must be recorded in order to be able to link it with the conditions recorded by other sources under which it occurred (e.g. traffic, weather conditions). If it is not possible for the system to be in constant operation (e.g. due to roadworks at specific days and times), it is important that there is eventually coverage of all times of the day and all days of the week, as it has been noticed that driving behaviour varies.

Further to the ability of the monitoring system to fulfil the goals described above, a series of additional parameters are taken into consideration, related to the procedures that need to be followed in order to install new technology on the motorway network. These procedures, followed by Balfour Beatty and Highways England, who are the network operators, ensure a new system is deployed in a safe and cost-effective manner and are followed during all deployment stages (pre-installation, design, installation, commissioning).

Without any constraints, an area would be monitored for HS incursion continuously in terms of space and time. When this is not feasible, the sections monitored are carefully selected in order to cover an extensive variety of conditions both in terms of construction characteristics (straight line/curve, uphill/downhill, various width of HS length, various width of main traffic lanes), as well as extending through all types of ambient conditions. Additional characteristics might be taken into consideration such as distance from junctions or being located before or after the motorway service areas etc. This might affect driving behaviour as closer to a junction the movements of the vehicles might not be ‘stable’ (e.g. trying to approach the exit). Also, it is expected that after the service areas, which offer a legal way to exit the motorway and rest, drivers would be less tired after having taken action to combat fatigue and, as a result, less prone to violations. The variety of locations depends on the ability of the equipment to be easily re-installed at a new site.

4.4. 4TH RESEARCH OBJECTIVE: DEVELOPMENT OF A HS INCURSIONS RISK MODEL

The fourth, and final, research objective is the analysis of the HS incursion occurrences and the development of a risk model for HS incursions based on the data collected from the monitoring system deployed on the network. The data are collated and processed to ensure quality, and are investigated in detail in order to determine any limitations and potential sources of error. The data are also compared with ground truth data, via camera footage which is manually reviewed, to identify the relationship between the two sources and calibrate the data collected by the HS incursions system. The risk model will define the probability that a HS incursion occurs at a specific location of a motorway, the underlying factors by which this is affected, and how the risk may change over time.

The first two research objectives have provided insight on the information to be collected so that the risk of HS incursions is explained. These explanatory variables are mainly infrastructure, traffic and weather related. Infrastructure variables refer to the slope, the horizontal curvature, the HS width as well as the number of lanes. The type of pavement surface will also be taken into consideration, as it will have an effect on the friction. All the above variables are collected from Balfour Beatty construction designs. Traffic related variables will be traffic flow and the proportion of HGVs, as well as speed (average and variance). The source of these will be Clearview Intelligence, the company that performs 365/24/7 traffic data collection on behalf of Connect Roads. The ambient conditions at the time of incursion are also important: weather, which will be collected from historical data, road surface conditions, visibility, lighting conditions. The explanatory variables and their data sources are summarised in Table 4.1.

These variables are then related to the incursions data in order to identify the riskier conditions. Models are formulated in order to increase our understanding of observed phenomena and they contain some basic assumptions from which conclusions are logically deduced. As such, models are a restricted form of general theories containing hypotheses and assumptions used to test these theories empirically. The ultimate goal of a road accident model is to identify variables that can be manipulated to reduce the number of accidents *(Hakim et al. 1991).*

Table 4.1 Explanatory variables and their data sources.

Category	**Explanatory variables**	**Source**
Infrastructure	Slope	Balfour Beatty Network Drawings (as constructed)
	Horizontal curve	
	Vertical Slope	
	Shoulder Width	
	Number of lanes	
	Type of pavement	Connect Roads Asset Manager
	Pavement quality	
	Rib line condition	Observation
Environment	Weather conditions	Met Office
	Visibility	
	Lighting conditions	Connect Roads Street Lighting
Traffic	Proportion of HGVs	Clearview Intelligence
	Traffic flow (per lane)	
	Speed (average and variance / real and permitted)	

Historically, a model that relates road traffic accidents with the factors affecting them has been useful for several reasons. Firstly, it has offered a more systematic and precise assessment of the relative contributions of factors associated with the road and its environment *(e.g. Agent, Deacon and Deen 1976),* the vehicles *(e.g. Newcomb and Spurr 1967),* the driver *(McDowell, Darzentas and Wennel, 1981)* and the pedestrian *(Robertson, 1966)* to the overall accident rates. In addition, it has enabled the relative role of individual causes of road traffic accidents to be more accurately analysed and has permitted similarity conditions to be specified for comparative studies of road traffic systems. This has also contributed to a greater insight into the complex interactions of causal factors in road traffic accidents and provided relatively easy explanations to many perplexing road traffic accident phenomena *(Asalor 1984).*

HS incursion events are random, discrete and non-negative, same as road accidents. Thus, methods applied in describing and predicting road accidents can be considered for appropriateness in this research. Recent studies have concentrated on the application of advanced statistical techniques (e.g. controlling for spatial dependency among adjacent segments, taking into account issues associated with nested accident data (i.e. multilevel modelling) so as to reliably investigate the contributory factors (i.e. geometric, weather and traffic characteristics) in explaining the variation in accidents *(e.g. Jones, Janssen and Mannerin,, 1991; Shankar, Mannering and Barfield, 1996; Caliendo.,Guida and Parisi, 2007; Lord and Mannering, 2010).*

A well-established technique is the Poisson-based probability model which seems to be appropriate here *(e.g. Joshua and Garber, 1990; Jones, Janssen and Mannerin,, 1991; Miaou and Lum, 1993; Miaou, 1994; Chin and Quddus, 2003).* However, the Poisson model has some potential problems due to the constraint of the mean being equal to the variance. If this assumption is not valid, the standard errors will be biased and the test statistics derived from the model will be incorrect *(Quddus, 2008)*. An alternative to the Poisson regression model would be the Conway-Maxwell Poisson model which might be more suitable as it was suggested by *Shmueli et al.* in *2005* and *Sellers and Shmueli* in *2010*.

It should be noted that the Conway-Maxwell Poisson is capable of handling both under-dispersion and over-dispersion in the data. Therefore, there is no need to use a Poisson-Gamma model, also known as Negative Binomial, which has been used in several studies. The estimation of parameters for the Conway-Maxwell Poisson generalised linear model though are challenging; this is because the likelihood equation for the Conway-Maxwell Poisson generalised linear model is relatively complex, making analytical and numerical maximum likelihood estimation difficult *(Lord, Guikema and Geedipally, 2008)*.

The performance of the Poisson and Negative Binomial regression models in establishing the relationship between HGV accidents and the geometric design of road sections was evaluated by *Miaou (1994)*. The Poisson and zero-inflated Poisson regression models were estimated using the maximum likelihood method, while the Negative Binomial regression model was estimated using the maximum likelihood, moment, and regression-based estimators. The Negative Binomial model based on the moment method was quite sensitive to the inclusion of short road sections. Under the maximum likelihood method, the estimated regression parameters from all three models were quite consistent and no particular model outperformed the other two models in terms of the estimated relative frequencies of HGV involvement accident involvements across road sections.

The Negative Binomial model performed the best in estimating the frequency of road sections with zero HGV accident involvement. The zero-inflated Poisson model, on the other hand, performed the best in estimating the frequencies of road sections with one, two, and three

HGV accident involvements. While the Poisson model performs the best in estimating the frequencies of road sections with four or more HGV accident involvements, the zero-inflated Poisson regression model appears to be a serious candidate model for studying the relationships when data exhibit excess zeros.

Poisson or Negative Binomial models assume that the observations are independently and identically distributed, which may not be true for accident data (and hence HS incursions); such data would be expected to be correlated over time within a particular area. In this study, the data will be highly disaggregated (15 minutes). However, well-established time-series modelling techniques such as Autoregressive Integrated Moving Average (ARIMA) modelling *(Jenkins and Box, 1976),* may not be suitable as this model imposes the normality assumption for the residuals. *Quddus (2008)* suggests that ARIMA models may be questionable especially when the average value of counts is low and the aggregated time-series is not highly aggregated with a large mean.

An alternative technique that was applied by *Brijs, Karlis and Wets (2008)* and *Quddus (2008)* to address this issue was the Integer-Valued Autoregressive (INAR) Poisson model; however, in this model time interdependencies were only controlled by a first order autoregressive term and no moving average term, indicating this technique is less flexible in controlling serial dependence in accident counts. In addition, this model cannot handle over-dispersed accident (or HS incursions) data and assumes that the time-series process is stationary.

Another technique proposed by *Davis, Dunsmuir and Streett. (2003)* to analyse discrete valued time-series with regression variables is the Generalised Linear Autoregressive and Moving Average (GLARMA) model. This combines the Generalised Linear (GL) and Autoregressive Moving Average (ARMA) processes. *Quddus (2016)* applied the GLARMA model to investigate the effect of Smart Motorways' introduction in GB on the accident levels suggesting its suitability. The GLARMA model is very appealing as it assumes that the count variable (number of HS incursions at a temporal unit) follow a Poisson-based distribution to address over-dispersion and, at the same time, allows the inclusion of explanatory variables in the model, and also autoregressive (serial correlation over time) and moving average (random) terms. The GLARMA model is discussed in more detail in ***§5.4***.

The following chapter describes in detail the research undertaken to achieve each of the research objectives within four work packages, summarised in Figures 4.6-4.7.

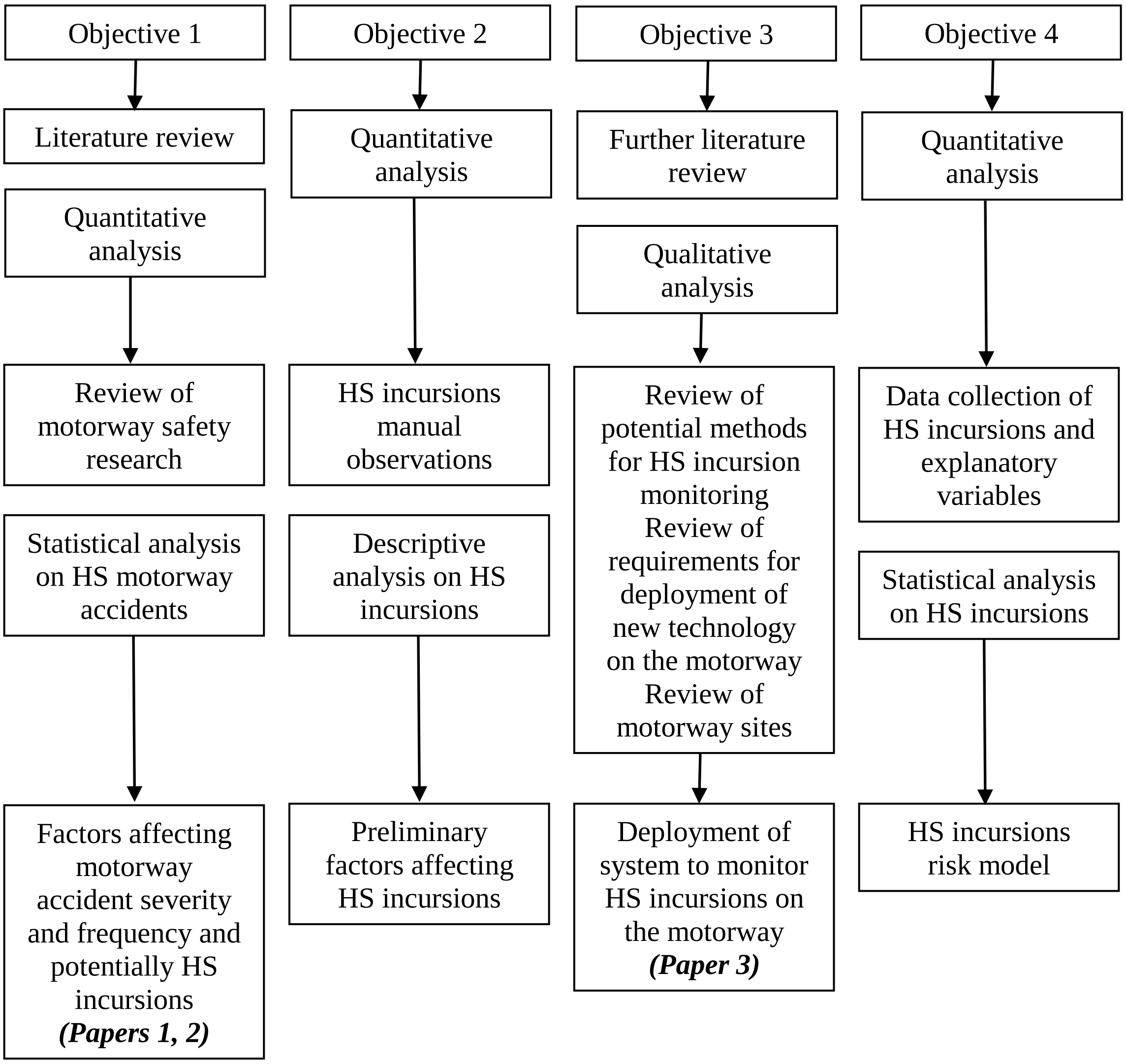


Figure 4.6 Summary of research objectives and methods adopted

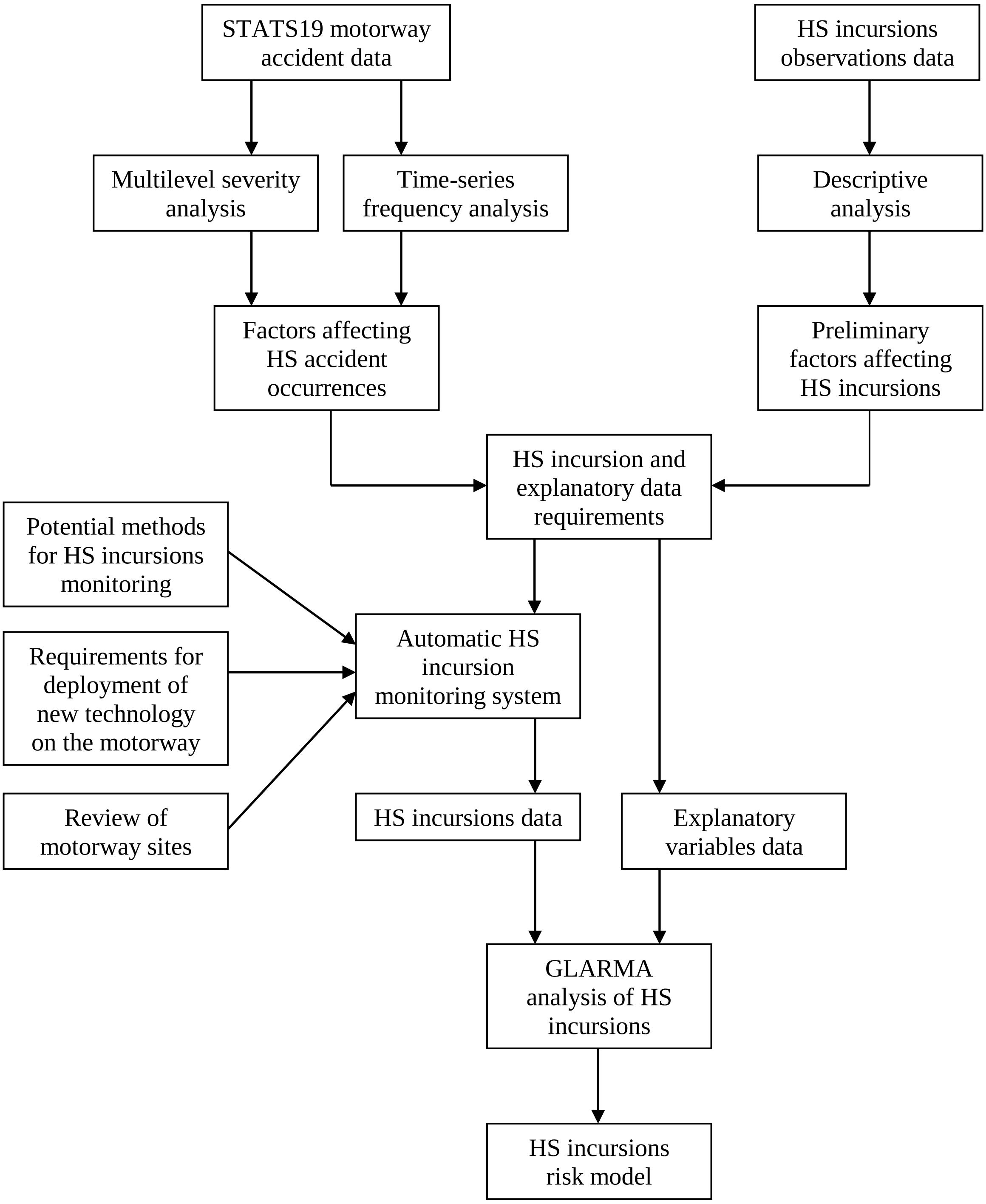


Figure 4.7 Flow diagram of the research methodology

5. RESEARCH UNDERTAKEN

This chapter provides an analysis review of the research undertaken and how this developed according to the objectives of the EngD project. The papers published during this research ***(Papers 1-3)*** are included in the Appendices (A-C).

5.1. INVESTIGATION OF HS ACCIDENTS

5.1.1. Scope and Aim

The first research objective is to investigate the motorway accidents occurring on the HS in terms of the factors that have an effect on their frequency and severity. Based on Heinrich's safety triangle (as explained in ***Chapter 4***), the factors that contribute to HS accidents are expected to provide an indication for the factors contributing to HS incursions.

5.1.2. Research Details

Most existing studies have focused on the total number of accidents that occurred on the motorways (also known as highways/freeways) rather than distinguishing HS accidents from the MC accidents *(e.g. Shankar, Mannering and Barfield, 1996; Lord, Washington and Ivan, 2005; Davis and Swenson, 2006; Golob, Recker and Pavlis, 2008; Wang, Quddus and Ison, 2009).* Although the width of the HS has normally been employed as a predictor of motorway collision frequency *(e.g. Noland and Oh, 2004),* there is a dearth of literature on HS accidents and consequently, there is little known about the scale of safety occurrences on the HS.

In GB, data related to all road accidents involving fatalities or personal injury, in which one or more vehicles are involved are collected. The police attend the scene and record the details which are organised into three datasets which include complete information on the accident itself, the casualties (any persons injured or killed) and every vehicle involved or contributing to the accident. The subsequent collated output reports, entitled STATS19, have been available since 1985.

The motorway accidents, including A-roads that have been upgraded to motorways, known as A(M) roads, are extracted and the separated according to the location where the *first* impact happened, the HS (entering, leaving or parked on the HS) or the MC. An accident where two vehicles on the MC collide and one ends up on the HS is not categorised as a HS accident. Over these 27 years, a total of 161,289 injury accidents occurred on the GB motorways of which 2.3% occurred on the HS. Even though the absolute frequency of HS accidents is relatively low, the percentage of HS accidents that are fatal is almost five times than for the MC and the proportion of serious injury accidents is also relatively high on HS (Table 5.1).

Table 5.1 Severity of accidents on motorways in GB.

Severity of accidents	***Hard-Shoulder accidents (1985-2011)***		***Main Carriageway accidents (1985-2011)***		***GB All Road accidents (2011)***
	Frequency	Relative Frequency	Frequency	Relative Frequency	Relative Frequency
Fatal	391	10.7%	3,647	2.3%	1.2%
Serious	912	25.0%	20,392	13.0%	13.8%
Slight	2,352	64.3%	133,595	84.7%	85.0%
Total	3,655	100%	157,634	100%	100%

5.1.2.1. Investigation of HS accident severity

The first part of this task is focusing on the factors affecting the severity of HS and MC accidents ***(Paper 1)***. For this investigation, STATS19 accident data from 2005 to 2011 are used and the unit of analysis is the accident. In the models developed, the severity of accidents (dependent variable) is associated with a series of explanatory variables, in separate models for HS and MC accidents.

Since 2005, the police have been recording additional data, often more subjective and related to drivers, vehicle or road characteristics; known as the contributory factors. These are factors in a road accident – in the opinion of the attendant police officer based on evidence – that are the key actions and failures that led directly to the actual impact. Up to six factors are recorded for each accident. They are clustered in certain categories according to STATS20; however, a different grouping is followed in this study, in order to minimise the number of categories and to create more cohesive groups, as further explained in ***Paper 1***. In addition, special focus is given to fatigue and a single category only for this is created, extracted from the 'impairment' category. The other categories refer to: driver error, driver behaviour, road conditions, vehicle, distraction and pedestrians.

The relative frequencies of some characteristics between HS and MC accidents are significantly different. For instance, out of all fatal accident, the percentage of those that involved driver's fatigue is double on the HS than the corresponding percentage for MC accidents (23.08% vs. 11.63%). Another such example for fatal accidents is the involvement of HGVs: in 80% of the fatal accident on HS, an HGV was involved, while for MC this percentage is only 44.36%. This is probably related to the vehicle weight and also the fact that more HGVs are travelling on lane 1.

A series of statistical models are considered for this analysis to correlate the accident severity to explanatory variables. Accident severity is usually recorded as a categorical variable. When the variable contains more than two categories, such as in the British system – slight/serious/fatal, the multinomial logit model can be used (*e.g. Khorashadi et al., 2005)*, and since the order of variables has a natural meaning, a commonly used model is an ordered logit *(Quddus, Wang and Ison, 2010)*. These models combine the independent variables to estimate the probability that a particular event will occur; in this case the probability of an accident to be slight, serious or fatal.

If the data are nested, such as accidents nested within roads and roads nested within areas (e.g. a census tract), the use of *multilevel ordered logit models* is more appropriate. Such models allow a possible correlation structure among a set of observations from the same level *(Dupont, et al., 2013; Lord and Mannering, 2010).* Based on the data hierarchy, the first decision concerns the choice of the levels of analysis. A level is a set of units, or equivalently a system of categories, or a classification factor in a statistical design. In these models, the inter-correlation among the accidents that occur in the same geographical area is captured. An area variable chosen to group correlated motorway accidents is counties, which derive from the geographical and administrative area division system in GB (Figure 5.1). Alternative hierarchy structures are the motorways (based on their whole length, regardless of the county) or motorways within counties (3-level model).

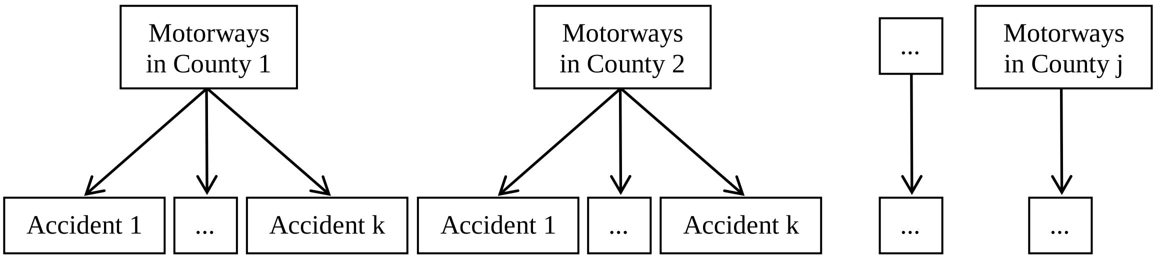


Figure 5.1 Example of multilevel model for motorway accidents in England

The multilevel mixed-effects ordered logit model allows for many levels of nested clusters of random effects. In this case, the coefficients of the model are not standard (fixed) for the whole sample, but they follow a distribution and conclusions are drawn about the population from which the observed units were drawn, rather than about these particular units themselves. The model is allowed to account for unobserved effects that are difficult to quantify and may affect the model estimation *(Ye and Lord, 2014).* In the two-level model, random effects of the accidents clustered in the English counties can be specified. For example, based on the first structure, the model estimates the possibility of an accident having a specific level of severity, given that the accident has occurred in a certain county - the second level of the model. Details of this modelling concept are discussed in ***Paper 1***.

The suitability of such models is tested using the Intra-class Correlation Coefficient (ICC). In cases where there is no identified inter-relationship among the observations, according to this test, a single level ordered logit should be used; however the parallel regression assumption needs to be tested using the Brant test. When the assumption is violated, an alternative model that allows for its relaxation should be preferred, such as the generalised ordered logit model, where the coefficients of the variable vary among the categories of the dependent variable *(Wang, Quddus and Ison, 2009; Eluru, 2013; Abegaz et al., 2014).*

After testing different level structures for the multilevel ordered logit model, the ICC has been found to be low suggesting a single-level model would be more suitable. However, the Brant test shows that the parallel regression assumption is violated, thus a generalised ordered logit model is then applied. The models for the MC and HS accidents are separately estimated while following the same process as above with the explanatory variables. Only the statistically significant variables at the 90% level are kept in the final models. The results are presented in detail in ***Paper 1***.

Accident Characteristics

For the MC model, the variables referring to the *number of vehicles, number of casualties* as well as *single-vehicle accidents* are statistically significant, while in the HS model, only the *number of casualties* appears to be significant, with a higher coefficient than MC. All these variables have a positive coefficient, increasing the accident severity.

Vehicle Characteristics

HGVs appear to have a positive coefficient, suggesting that the severity of a HS or MC accident is increased when at least one HGV vehicle is involved in the accident. This is because the resulting impact is more serious *(Öz, Özkan and Lajunen, 2010)*. On the contrary, *left-hand-side driving vehicles* tend to reduce the level of severity of accidents, which may be attributed to more cautious driving in a non-familiar road environment.

Seasonality

It has been found that during *working days*, the accidents are of lower severity than during the weekend. Past studies have not been consistent and conclusive on this; for instance, *Quddus, Wang and Ison (2010)* concluded that accidents on the M25 motorway, around London, are more severe on weekdays, while *Gray, Quddus and Evans (2008)* suggested the opposite, which is consistent with the results of the models estimated.

Traffic Characteristics

Proxy variables are used to represent traffic characteristics based on historical data: *peak in the morning*, the *late afternoon peak*, *normal* and *non-peak* (quiet) traffic hours. The results suggest that during non-peak hours, severity tends to be higher, which could be related to the average speed *(Elvik, Christensen and Amundsen, 2004).* In addition, higher speed limits are related to an increase of road accidents' severity level.

Conditions on the Motorway

The presence of *lights* (daylight or street lighting) reduces the accident severity, while good *pavement conditions* have the opposite effect. Fine *weather conditions* are also significant for severity in an increasing manner, while *wind* was tested but not included in any of the final models. When *roadworks* are present, the severity of accidents tends to drop; this can be linked to the speed restrictions that are always imposed in these instances and higher driver awareness. It is noted that if an accident happens in a closed lane that is normally running, the accident is considered a HS accident.

Contributory Factors

All contributory factors are represented by a group of dummy variables; the variables representing the factors related to the ‘road’ is excluded from the model for the other variables to be compared with. All variables of contributory factors have a positive coefficient, indicating that their presence increases the accident severity. The highest coefficient is the one related to ‘pedestrians’ involved in the accident, which is attributed to the vulnerability of this group of people. Distraction and driver fatigue are also statistically significant factors for both the MC and HS models, though fatigue is more important for HS accidents. Past studies have shown that HGV drivers often feel tired while driving *(e.g. Häkkänen and Summala, 2001)*, as a result of long and monotonous journeys or timetable restrictions precluding drivers from taking adequate rest breaks. Error and behaviour related factors have a very high correlation, often appearing in an accident together.

5.1.2.2. Investigation of HS accident frequency

A second study is presented in ***Paper 2***, the primary objectives of which are to examine the motorway accidents over time and to investigate various control and exposure variables affecting such accidents that can potentially explain the evolution of the two different series (HS and MC accidents).

The factors that appear to affect road accident likelihood are generally divided into two categories: engineering (e.g. road infrastructure characteristics, traffic and weather conditions) and human (e.g. driving groups, driver age, gender, impairment, fatigue), which have been discussed further in ***§3.1***. HGV drivers as well as younger drivers have been proved to be a high risk group *(e.g. Charbotel, Martin and Chiron., 2002; NHTSA, 2008; Hassan and Abdel-Aty, 2013)*. The same applies to male drivers as well as drivers under alcohol impairment *(e.g. Evans, 1991; Holubowycz, Kloeden and McLean, 1994; Constantinou et al., 2011)*. Driver fatigue also appears to be an important accident factor, especially for HGV drivers *(e.g. Nordbakke and Sagberg, 2007; Zhang and Chan, 2014)*. For this reason, the Motorway Service Areas (MSAs) are designed to provide a safe exit and rest areas for drivers using the motorway network *(Motorway Services Online, 2015)*.

To investigate the evolution of road accidents over time and investigate the contributory factors to explain the variation, time-series modelling techniques are applied. A well-established choice for detecting patterns, trends and seasonality is the Autoregressive Integrated Moving Average (ARIMA) model proposed by *Jenkins and Box (1976)*, which has been suggested to perform well in dealing with aggregated time-series count data *(Quddus, 2008)*. However, this model does not allow combining and examining two time-series simultaneously. The cross-correlation function, which has been used in time-series modelling *(e.g. Haugh, 1976; Lopez-Lozano et al., 2000; Pitfield, 2005; Zebende and Filho, 2009; Brockwell, 2010; Zebende, Da Silva and Filho, 2011)*, provides a means for testing the hypothesis that two stationary time series are independent *(e.g. Koch and Yang, 1986; Duchesne et al., 2011)*.

An alternative technique, which has been widely used for multiple time-series analysis, is the Vector Autoregressive (VAR) model *(e.g. Quenouille, 1957)*. This model also allows for exogenous (explanatory) variables to be included *(e.g. Lütkepohl**,** 2005)*, which can be related to, and possibly explain, the trends that the time-series accident follows. Several past studies have incorporated explanatory variables to investigate the correlation between road and driver characteristics, as well as weather conditions and the frequency of road accidents *(e.g.*

Beenstock and Gafni, 2000; Bergel-Hayat et al., 2013; Gomes, 2013; Theofilatos and Yannis, 2014). Details of this modelling concept are provided in ***Paper 2***.

The VAR model fits a multivariate time-series regression of each dependent variable on lags of itself and on lags of all the other dependent variables. The lags are treated as explanatory variables. A variant of the VAR model can also be used to allow the inclusion of exogenous variables in the regression to possibly explain the evolution of the dependent ones, known as VAR(X). The cointegration of the dependent variables also needs to be tested, as this would indicate any linear relationship between them. If one exists, a variation of the VAR model, known as the Vector Error Correction (VEC) model would be used, which contains the cointegration relations. For this check the Johansen's test may be used *(Johansen, 1991)*.

In VAR models, the restriction of stationarity is not imposed before applying the model, the residuals of the models are checked for non-stationarity. In addition, the Lagrange multiplier (LM) test for autocorrelation in the residuals resulting from the VAR model can be employed *(Johansen, 2005)* in the post-estimation phase. The null hypothesis is that there is no autocorrelation between the residuals. In order to investigate whether one series can cause the other, the Granger causality test can be employed. A variable x is said to Granger-cause a variable y if, given the past values of y, the past values of x are useful for predicting y *(Granger, 1969)*, which can be tested using Wald tests. Failure to reject the null hypothesis is equivalent to failing to reject the hypothesis that x does not Granger-cause y.

The VAR model is applied on the HS and MC monthly time-series simultaneously to reveal any differences in the way they have evolved throughout the years, while lags and exogenous variables are included. Both series generally follow similar increasing/ decreasing patterns. There is also strong seasonality in MC accidents series with both upward and downward trends, while HS accidents steadily decrease over the study period. In addition to the dependent variables, the number of monthly accidents, data for exogenous variables that could possibly explain the variation of the collision frequency throughout the years are collected, related to the use of motorways, the infrastructure, vehicle and driver characteristics, as well as weather conditions. For data consistency across the variables, the data are collected from 1993 (when the method of historical traffic data collection on British motorways changed) or otherwise from when these have become available. The sources of data are all available online: *Department of Transport (DfT)* in the UK, the *UK Met Office*, *HM Treasury* and *Motorway Services Online*. In summary, the data collected are:

Motorway traffic

- *Vehicle miles travelled (VMT)* (1993-2011) on motorways in the UK by year in millions which increased steadily until it becomes stable after 2006. It is used as an exposure measure.
- *Percentage of miles travelled by HGVs* (1993-2011) on motorways in England by year. HGVs appear to be involved in a high percentage of motorway accidents, especially in the case of HS. Even though, the absolute value of VMT by HGVs has been increasing, the percentage has been decreasing while a small peak is observed in 2010.
- *Percentage of cars exceeding the speed limit* (2002-2011) on motorways in the UK (overall or by more than 10mph) by year. The speed limit on UK motorways is normally 70mph (113 km/h). Cars exceeding the speed limit by more than 10mph (16km/h) are selected as an indicator of the driver’s behaviour. Both percentages have been slowly decreasing showing a general improvement in drivers’ compliance.

Infrastructure characteristics

- *Motorway Service Areas (MSAs)* (1993-2011) in the UK, which is defined as the number of MSAs per 100 miles of motorways. Since the first MSAs opened in 1959, new ones have been installed across the country. There has been a 43% increase between 1993 and 2011.

- *Total length of motorways* (1993-2011) in GB in miles by year (same for HS and MC for the years examined). There has been an 11% increase in the total length of British motorways between 1993 and 2011.
- *Road surface condition* (2003-2011) in England by year, defined as the percentage of lane 1 length (next to the HS) surveyed requiring further investigation. This is stable until 2008, when a significant decrease is noticed.
- *Public expenditure on transport* (1993-2011) in the UK by year, in which there has been a fluctuation throughout the years. The values were adjusted to 2012-13 price levels using Gross Domestic Product (GDP) deflators from the Office for National Statistics in the UK.

Vehicle characteristics

- *Total number of vehicles* (1994-2011) registered in the UK by year, which has been constantly increasing within the data collection period.
- *Average age of cars* (1994-2011) registered in the UK by year, which increased until 1997 and then again after 2004. This represents the progression of technology in the car industry, which might be related to the reduction of motorway accidents.

Drivers' characteristics

- *Percentage of population per age group that hold a driving licence* (1993-2011)in the UK by year
- *Percentage of trips by young drivers* (aged from 17 to 29) (1993-2011) in the UK by year
- *Percentage of miles travelled per age group* (1993-2011) as a car/van driver by year

These variables are included to control for driver experience. The most representative variable is the one referring to the miles travelled; however, this information is only available since 2002. In the study, focus is on the miles travelled by young drivers. A drawback of this data is that the trips/miles do not only refer to motorways; however; the assumption is that they still capture the general level of experience of a driver.

Weather conditions

- Total precipitation (1993-2011) in the GB in mm by month
- Average temperature (1993-2011) in UK in Celsius degrees by month
- Total hours of sunshine (1993-2011) in UK by month

According to previous studies *(e.g. Hermans et al. 2006; Caliendo, 2007)*, a correlation between increased collision frequency and either total precipitation, temperature or sunshine hours is expected. However, opposite results for the effect of precipitation have, to a smaller extent, also been stated by others *(e.g. Karlaftis and Yannis, 2010; Bergel-Hayat, 2013)*. The precipitation data were available for England + Wales and Scotland separately. Weighted average values were used according to the length of the motorways, as in Scotland their lengths are limited in comparison to the rest of GB (England and Wales contain 87% of the British motorway network).

In the pre-estimation phase, a set of model criteria are estimated without any exogenous variables. This is applied for each of the models, including lags up to 12. In addition, the existence of the cointegration equation is tested for several forms of the dependent variables, such as the number of MC and HS accidents, their natural logarithms and their first and seasonal differences. Based on the final prediction error (FPE) (***Lütkepohl, 2005)***, Akaike's Information Criterion (AIC) *(Akaike, 1973; 1974)*, Hannan and Quinn Information Criterion (HQIC) *(Hannan and Quinn, 1979),* 12 lags should be included in the model for all cases of dependent variables. Only the Bayesian Information Criterion (BIC) *(Schwarz, 1978)* suggests the use of 2 lags. When the natural logarithms of the dependent variables are taken and 12 lags are included, there are no cointegration equations; suggesting that the VAR model can be used, while the stationarity of residuals is tested at the end.

The final results VAR(X) Models for MC and HS motorway accidents are using data from 1993 to 2011, as allowed by the exogenous variables availability. Models including exogenous variables available since 2003 were also tested; however a more suitable model was not indicated. Due to autocorrelation between the residuals, some of the lags were excluded from the model. When the residuals of the model estimated are tested for stationarity, no correlation pattern is observed suggesting that the VAR model is valid. The Lagrange-multiplier test also suggests no misspecification of the model.

The results (see ***Paper 2*** for details) show the relationships MC lags on MC accidents and HS lags on HS accidents. There is a positive relationship between the values of a month with the corresponding month of the previous year, which suggests that there is monthly and annual seasonality in MC accidents. In addition, a negative relationship is expected between current values and values 6 months later. Accordingly, seasonality in the HS series (HS-HS) is not apparent in this model, as none of the coefficients are significant.

The simultaneous modelling of the two series provides the opportunity to relate the current values of one series to the lags of the other. Several coefficients of the HS lags are statistically significant; more specifically lags 2, 5 and 6. For instance, the value of lag 6 coefficient for MC-HS is negative, showing that there is an opposite trend between the current values of MC accidents and the values of HS accidents six months before. The same applies in the case of HS accidents being the dependent variable, where a significant positive coefficient of lag 12 suggests that when the values of MC accidents have increased, the values of HS accidents in a year's time will also increase, although this does not mean that there is any cause-causality relationship implied. The Granger test results suggest that the trend of HS accidents does not have a strong relationship with MC accidents, showing that the two series have to be examined separately.

Out of all the exogenous variables investigated in this model, some appear to be significant in the equation of MC accidents and one of them for the HS accidents. The proportion of vehicle miles travelled by HGVs on motorways has a positive relationship with the evolution of accidents confirmed by the positive coefficient and statistically significant value. This finding is in line with other existing studies *(e.g. Charbotel et al., 2002)*. Due to multi-collinearity, the proportion of HGVs could not be included in the model along with the total vehicle miles travelled.

Regarding the weather conditions, it is suggested that both precipitation and hours of sunshine per month increase the number of MC accidents. It is supported that rainfall and snow are associated with a higher number of accidents, which is in line with other studies *(e.g. Antoniou, Yannis and Katsochis, 2013)*. In addition, the hours of sunshine per month appears to have a positive relationship with the number of MC accidents, also suggested by past studies *(e.g. Hermans, 2006)*. Under rainy conditions, lower visibility is expected as well as a higher risk of slipping/losing control of the vehicle. On the other hand, sunny weather can be linked with a higher likelihood of glaring, especially on the motorway. Also, from a behavioural point of view, drivers can become less careful and concentrate less when the conditions on the road appear good, hence 'safe'.

5.1.3. Key findings

The outcome of this objective is to examine the factors that are expected to have an effect on the likelihood and severity of HS incursions based on two studies: (1) accidents occurred on HS and (2) accidents occurred on MC using STATS19 motorway accident data in GB. To summarise, the factors that appear significant for these two accident groups are not the same. Accidents on the HS in particular are more severe during weekends, non-peak hours and good pavement conditions while the presence of lights and roadworks has the opposite effect. When an HGV is involved, the severity tends to increase and also when fatigue is identified as a contributory factor. This is also linked with the presence of MSAs, which reduces the risk for HS accidents.

5.2. HS INCURSIONS SURVEY DATA

5.2.1. Scope and Aim

Further to the investigation of motorway accidents on the HS and MC, the second research objective is to explore the factors affecting the occurrence of HS incursions using preliminary information. Using observation data from road users we gain better knowledge on the contributory factors specifically for HS incursions that need to be considered in the next steps of the research. The next steps will involve the monitoring of HS incursions by an automatic monitoring system and the analysis of these occurrences with the help of explanatory variables. This work package is going to assist further with identifying these explanatory variables that need to be tested.

5.2.2. Research Details

Balfour Beatty Construction Services is Balfour Beatty’s division undertaking major infrastructure projects, including highways projects. As part of the ZH Initiative, which was launched in 2008 to methodise the company's policies and measures to eliminate fatalities and serious injuries, all Balfour Beatty's departments were asked to identify their five top risks for their employees, and to investigate ways of controlling and reducing them. In this context, Balfour Beatty Construction Services identified as one of their major risks their road-workers face was being hit by an oncoming vehicle while performing their tasks on the HS of the motorway. Therefore, they expressed interest in taking action towards eliminating this hazard and they formed a specific focus group for this purpose, chaired by a Director.

Balfour Beatty Construction Services, as the Asset Support Contractor for Highways England's Area 2 until 2012, participated in this research's survey conducted in the area in order to collect HS incursions data from their own observers. Area 2 covers the South West of England, from Tewkesbury to Exeter and from Swindon to Wales and includes, amongst others, motorways M4 and M5 (Figures 5.2, 5.3). The observers were operatives driving Balfour Beatty Construction Services' vehicles on the network (as described in ***§4.2.2***). While patrolling and driving to work sites, they were noticing vehicles invading the HS and filled in appropriate forms, including information related to the occurrences, trips and conditions:

HS incursions

- Number of occurrences
- Severity of occurrences

Trip characteristics

- Date
- Junctions of entering and exiting the motorway and direction
- Time that the trip on the motorway started
- Duration travelling on the motorway

Conditions

- Daytime/night-time
- Visibility good/poor
- Pavement condition

This survey included 185 trips and 296 hours of observations in total. Trips were mainly performed on the M4 and M5 motorways, plus parts of M32, M48 and M49. A total of 192 incursions were recorded. The majority (81%) were recorded as slight (just over the rib-line) and 19% were recorded as serious (well over the rib-line), as defined in ***Chapter 4 (§4.2)***. In terms of the driving conditions, three different alternate cases were examined; dry or moist/wet pavement; daytime or night-time while driving; and lastly, the level of visibility. Tables 5.2-5.7 show the number of trips (also converted into hours according to the recordings) with the different conditions.

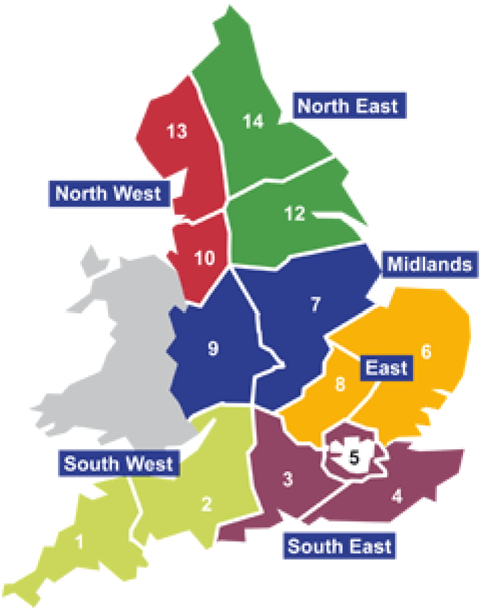


Figure 5.2 Map of Highways England's areas *(source: Highways England)*

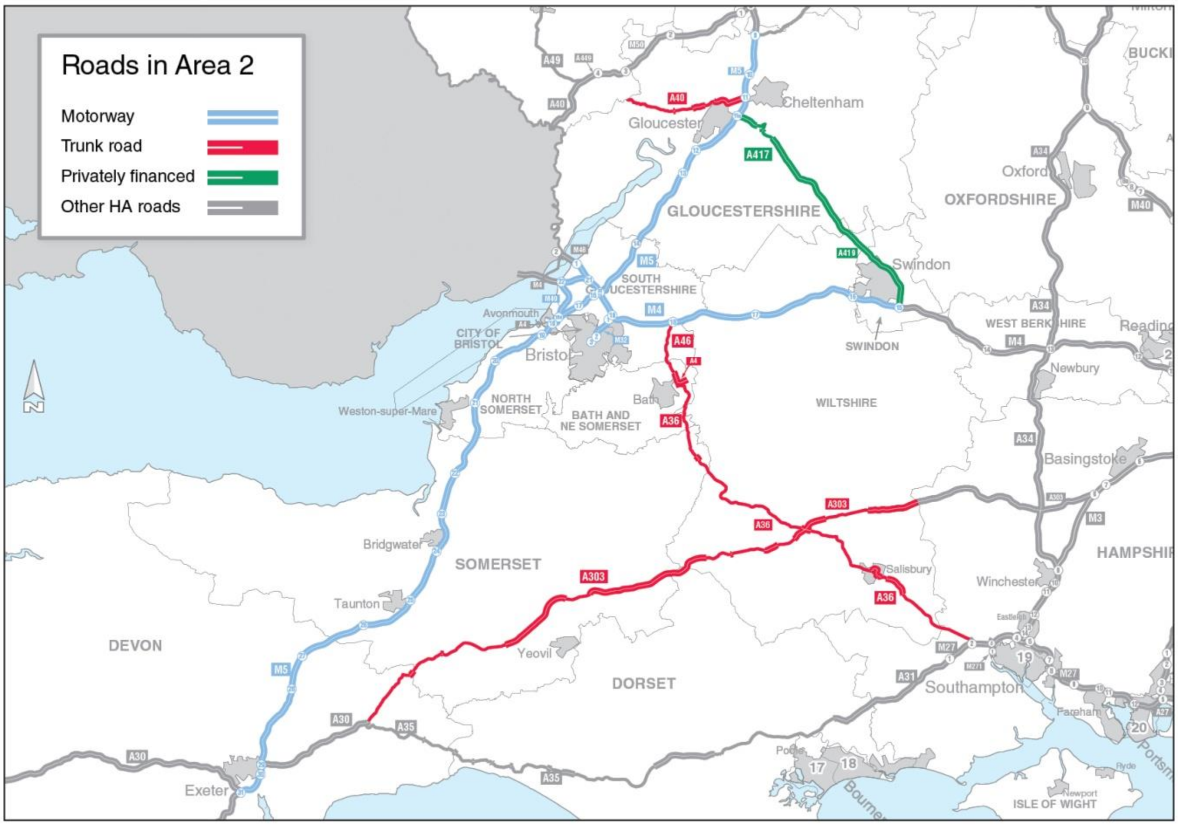


Figure 5.3 Map of Area 2 *(source: Highways England)*

Pavement conditions

The pavement condition is defined as dry or wet. During dry pavement conditions, 83% of the incursions observed were slight and 17% serious. Rates were similar for the case of wet conditions (81% and 19% respectively). More incursions were observed when the pavement is wet. At a particular location, approximately 0.5 slight incursions per hour (or 1 per 2 hours) were observed when the pavement was dry with 1 serious per 10 hours at a particular location. With wet pavement, 30% more slight incursions were recorded and 50% more serious ones. Figures 5.4-5.5 compare the percentages of slight and serious HS incursions while the pavement is dry or wet.

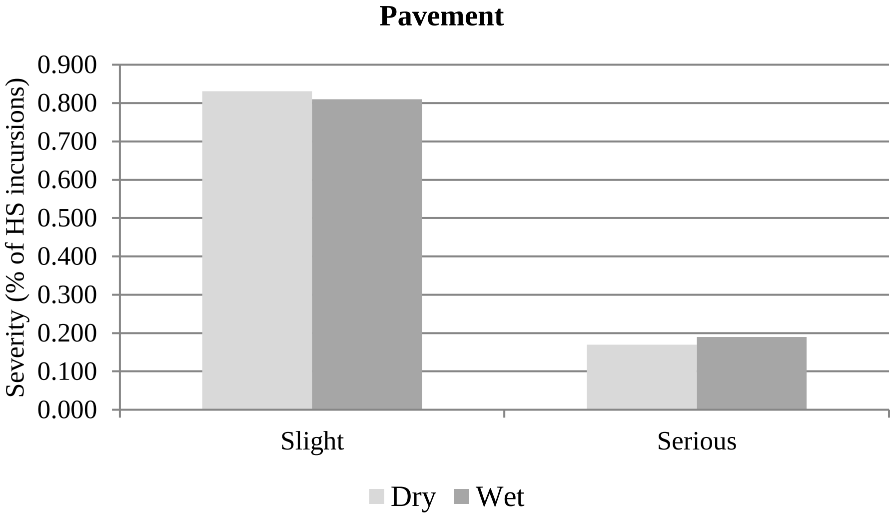
Tables 5.2-5.3 HS incursions observations by pavement conditions.

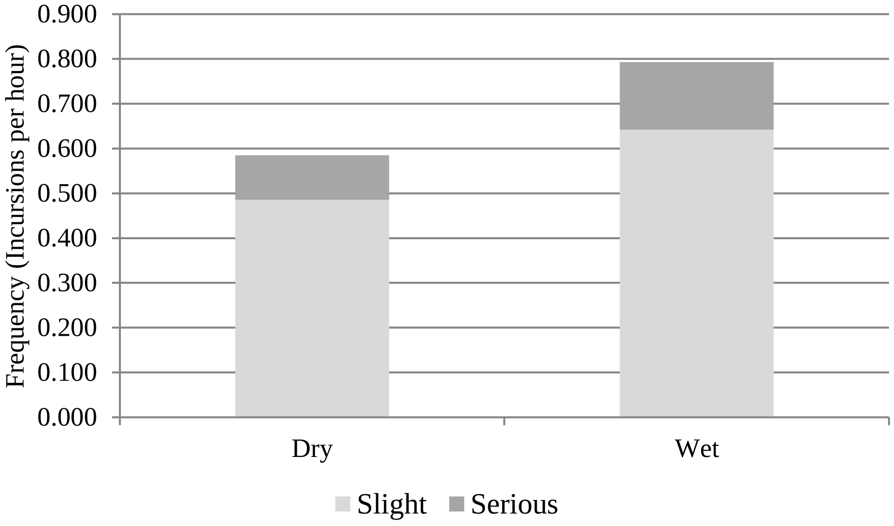
HS incursions severity by pavement conditions

Condition	Slight		Serious		Total	
	#	rel. freq.	#	rel. freq.	#	rel. freq.
Dry	103	83.1%	21	16.9%	124	100%
Wet	47	81.0%	11	19.0%	58	100%
Dry/Wet	6	60.0%	4	40.0%	10	100%
Total	156	-	36	-	192	-

HS incursions frequency by pavement conditions

Condition	Hours of Observation	Slight		Serious		Total	
		#	inc/hour	#	inc/hour	#	inc/hour
Dry	212.09	103	0.486	21	0.099	124	0.585
Wet	73.16	47	0.642	11	0.150	58	0.793
Dry/Wet	11.00	6	0.545	4	0.364	10	0.909
Total	296.25	156	0.527	36	0.122	192	0.648





Figures 5.4-5.5 HS incursions observations severity and frequency by pavement conditions

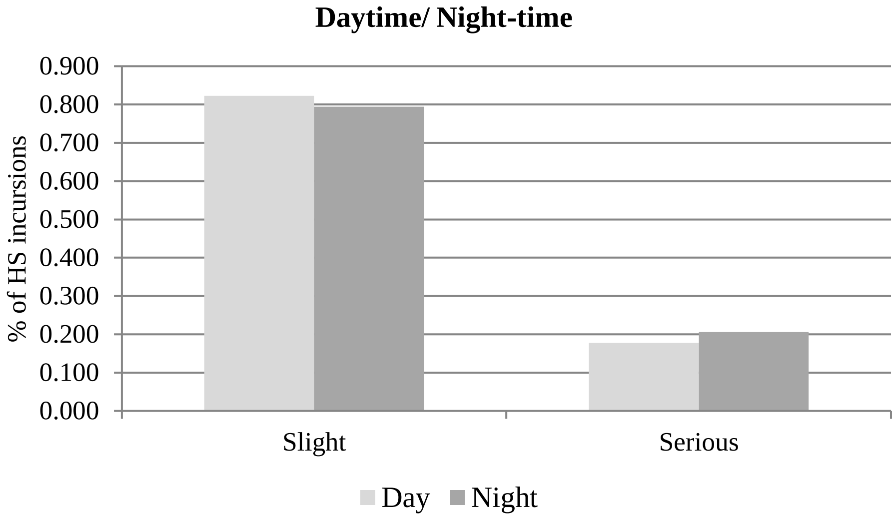
Daytime/Night-time

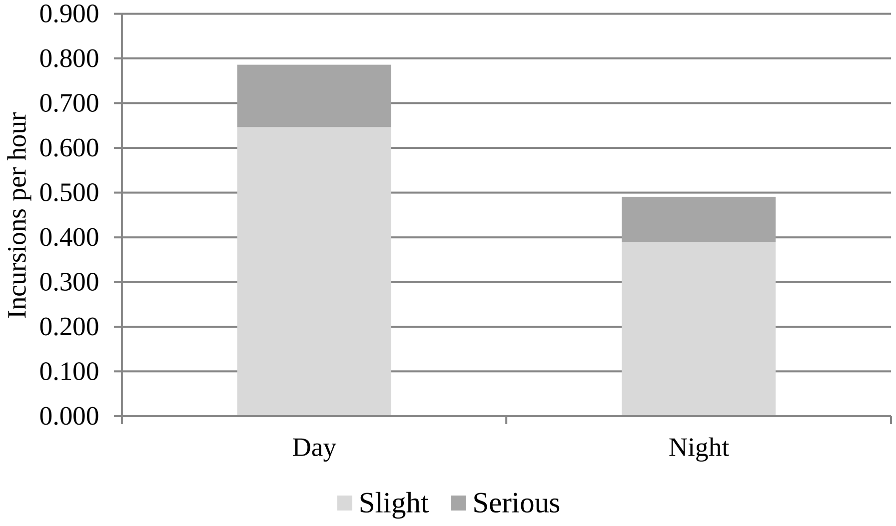
When incursions are examined in relation to the time of the day (daytime/night-time), the severity appears to be similar, with 17.7% being serious during daytime and 20.6% during night-time. However, the frequency of incursions per hour of observation differs during daytime and night-time. Overall, 0.786 incursions occur per daytime hour, and 0.491 incursions per hour at night-time in a motorway stretch. The slight incursions are 66% probable to occur in the daytime, while serious incursions are 38% more probable. Overall, at a specific location there is a 60% higher probability for an incursion to happen during the daytime (Tables 5.4-5.5). Further investigation is required on this, as it may result from the inability of the participants to observe the events during night-time, especially over long distances. Figures 5.6-5.7 compare the incursions severity and frequency at day and night.

Tables 5.4-5.5 HS incursions observations by daytime/night-time.

HS incursions severity by daytime/night-time						
Condition	Slight		Serious		Total	
	#	rel. freq.	#	rel. freq.	#	rel. freq.
Day	102	82.3%	22	17.7%	124	100%
Night	54	79.4%	14	20.6%	68	100%
Total	156	-	36	-	192	-

HS incursions frequency by daytime/night-time							
Condition	Hours of Observation	Slight		Serious		Total	
		#	inc/hour	#	inc/hour	#	inc/hour
Day	157.75	102	0.647	22	0.139	124	0.786
Night	138.50	54	0.390	14	0.101	68	0.491
Total	296.25	156	0.527	36	0.122	192	0.648





Figures 5.6-5.7 HS incursion observations severity and frequency by time of the day

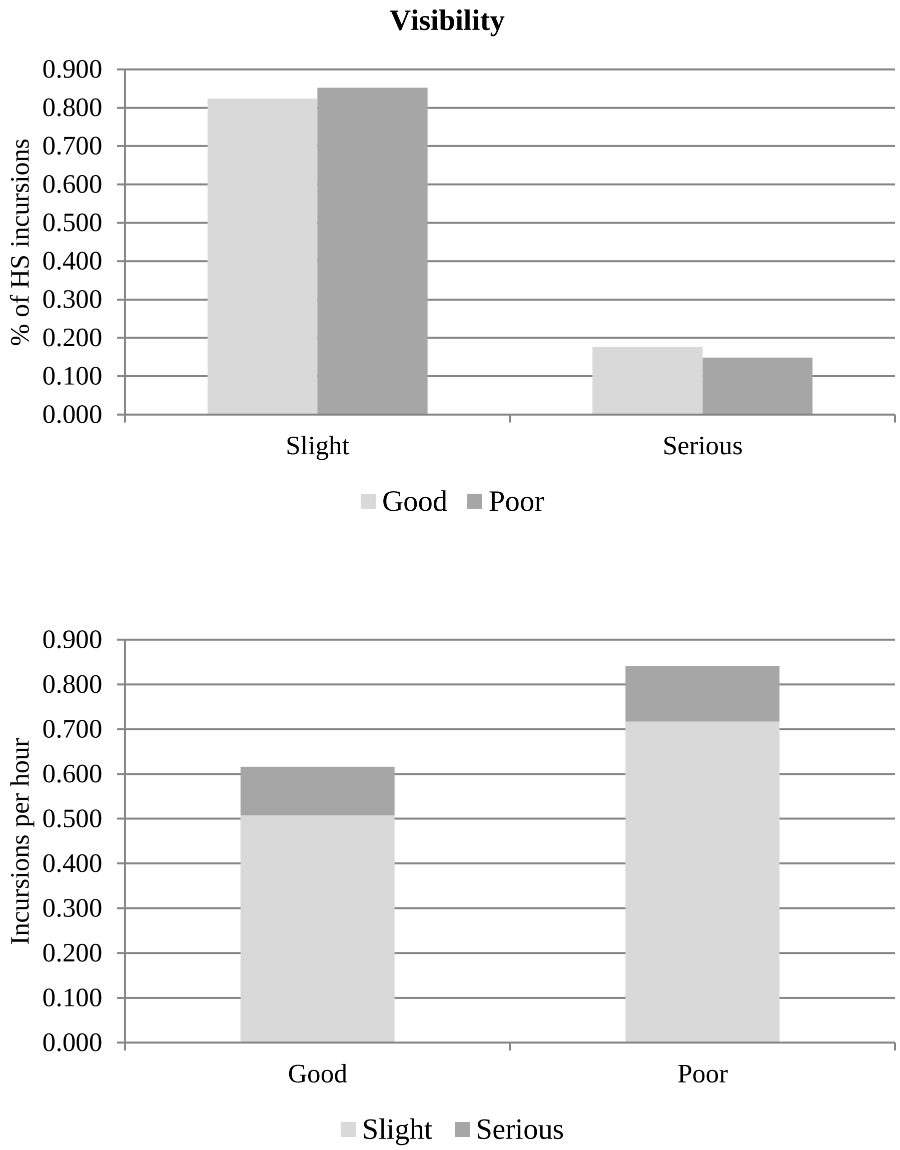
Visibility

When the driving conditions were more challenging, i.e. visibility was poor; the percentage of serious incursions recorded was similar to slight. Under good visibility conditions, 82.4% of incursions were slight, while the corresponding value for poor visibility conditions was 85.2%. Under good visibility, 1 incursion per 2 hours was noticed at one particular location, while the frequency was 41% more when the visibility was poor (Tables 5.6-5.7). The difference between good and poor visibility conditions was lower in the case of serious incursions (Figures 5.8-5.9).

Tables 5.6-5.7 HS incursions observations by visibility conditions.

HS incursions severity by visibility conditions						
Condition	Slight		Serious		Total	
	#	rel. freq.	#	rel. freq.	#	rel. freq.
Good	126	82.4%	27	17.6%	153	100%
Poor	23	85.2%	4	14.8%	27	100%
Good/Poor	7	58.3%	5	41.7%	12	100%
Total	156	-	36	-	192	-

HS incursions frequency by visibility conditions							
Condition	Hours of Observation	Slight		Serious		Total	
		#	inc/hour	#	inc/hour	#	inc/hour
Good	248.17	126	0.508	27	0.109	153	0.617
Poor	32.08	23	0.717	4	0.125	27	0.842
Good/Poor	16.00	7	0.438	5	0.313	12	0.750
Total	296.25	156	0.527	36	0.122	192	0.648



Figures 5.8-5.9 HS incursion observations severity and frequency by visibility conditions

5.2.3. Key findings

The purpose of this work package was to gain some knowledge on the frequency and severity of HS incursions, based on observations from the motorway. In addition, information on the conditions under which these incursions occurred was collected. It was shown that within a stretch, 2 incursions were observed every 3 hours (0.648 incursions per hour). In terms of the driving conditions, the severity of incursions is slightly higher during dry pavement conditions, night-time hours and under good visibility. More incursions were observed when the pavement was wet, however the frequency was lower during the daytime and also when the visibility was good. The next step of the research is the implementation of a system on the motorway that will automatically collect HS incursions data. The conclusions of the second work package indicate a HS incursions frequency and also that the driving conditions need to be further examined and linked to the occurrences to investigate their effect on incursion risk.

5.3. IMPLEMENTATION OF A DATA COLLECTION SYSTEM FOR HS INCURSIONS

5.3.1. Scope and Aim

Further literature review has been conducted in order to identify potential solutions for an automatic HS monitoring system and deploy a suitable system ***(§ 3.2)***. In addition to this, in this work package, the parameters for the deployment of a new system on the M1-A1 Link Road are investigated to ensure that all the requirements are followed and limitations are known. The trial system implemented for the collection of HS incursions data is analytically described. The work conducted in this package was summarised in ***Paper 3***.

5.3.2. Research Details

5.3.2.1. Considerations for installation of new technology on the motorway network

Highways England produces Standards relating to the design, construction and maintenance of highways. These need to be followed when installing any new piece of equipment on the network. Specifically, the Design Manual for Roads and Bridges (DMRB), which is part of the Standards for Highways, is a manual containing information about current standards, advice notes and other published documents relating to the design, assessment and operation of motorways and all-purpose trunk roads *(DMRB GD 01/15, 2015).*

A *Departure from Standard* is issued when the Standard, including permitted Relaxations, is not realistically achievable. Relaxations are permitted by the Standards in difficult circumstances and are introduced where experience has shown that certain requirements may be varied within defined limits in particular situations. Proposals to adopt Departures from Standard are submitted to Highways England for approval before incorporating into a design layout. *(DMRB GC 01/15, 2015; DMRB TD 27/05, 2005).*

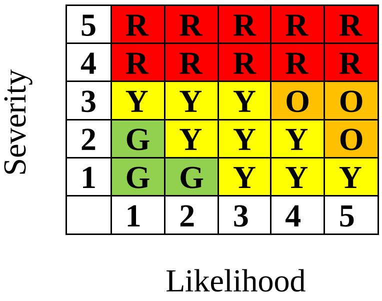
Safety, Engineering and Standards (SES), formerly called Professional and Technical Solutions (PTS), is the department of Highways England responsible for supporting the operational delivery of the road network by specifying the procurement of all services, developing standards and methodologies as well as providing technical advice. When new equipment is installed on the motorway, approval from SES may be required. However, since Connect Roads has a DBFO contract with Highways England, it is permitted to make decisions on the deployment of new technology as long as safe procedures are followed. Standards are followed (see ***Appendix B*** for more details) and proposals submitted for consideration by Highways England via the Review Procedure outlined in the contract.

5.3.2.2. Balfour Beatty procedures for the deployment of a HS monitoring system

Risk assessments and method statements

The risk assessment is the document listing all the possible Health, Safety and Environment hazards for a specific task. After the process of the task is described, all the potential risks are identified (through brainstorming). The cause and consequence of each risk are clearly defined and their severity and likelihood estimated. Based on the risk classification matrix used by Balfour Beatty, the trigger colour (red-amber-green) is defined (Table 5.8). At this stage, mitigation measures are proposed to minimise the residual risk and create an action plan. When the severity of a risk is of level 4 or 5, it is categorised as Red (R) regardless of its likelihood, which is not acceptable and further mitigation measures are required to reduce the risk to an acceptable level.

Table 5.8 Risk Classification Matrix used in Balfour Beatty risk assessments.



5	R	R	R	R	R
4	R	R	R	R	R
3	Y	Y	Y	O	O
2	G	Y	Y	Y	O
1	G	G	Y	Y	Y
	1	2	3	4	5

After the risk assessment has been agreed, the method statement is conducted to show step by step how a task will be safely performed. The method statement should be strictly followed during the whole process to minimise the risk.

Operations on motorway site

To work on-site, it is required by Balfour Beatty to obtain the Constructions Skills Certification Scheme (CSCS) card. This provides proof that individuals working on construction sites have the required minimum level of training and qualifications. There is a range of CSCS cards to reflect varied occupations in construction according to the level of experience and the qualifications of the individual. To obtain a card, the *Health Safety and Environment Test* is required, organised by the Construction Industry Training Board (CITB). The test has two levels (Operatives & Supervisors or Managers & Professionals) according to the card desirable and includes behavioural case studies and knowledge questions. For this project, the Managers & Professionals test was passed and an Academically Qualified card was issued. Although being a cardholder, it is always required to be escorted on site by at least one experienced person. Balfour Beatty Major Projects – Highway Services is the department of Balfour Beatty responsible for the maintenance of the network. The Director has agreed that the operatives provide all the assistance required for the installation and operation of the equipment at no additional cost.

To summarise, for the installation of new equipment to be allowed on the network, the following must be fulfilled:

- All the requirements according to the Standards of Highways England are followed;
- All the internal Balfour Beatty procedures are followed and the Operations Manager agrees with the deployment of the system;
- The installation and operation of the equipment is being performed by a competent person (training required);
- H&S requirements are fulfilled, after consultation by the HSE;
- The police, Clearview Intelligence (the sub-contractor responsible for traffic data counting on behalf of Connect Roads) and all related organisations/operators (including Highways England when required) are informed about the existence of new equipment on the network and its purpose prior to its installation.

Apart from the requirements of Highways England and Balfour Beatty, there are further parameters for the site and equipment type selection. The *resources* that are available on-site are important for both the site and equipment selection. For example, power can be used to facilitate the installation and operation process. Other resources might include existing infrastructure (e.g. CCTV cameras) which could be useful for data calibration. In terms of *safety* and *security*, the requirements imposed by Highways England and Balfour Beatty must be met, which might affect the location and the technology selection. The less interventions and ‘risky’ actions the equipment require for installation, operation and maintenance, the more preferable it becomes. Regardless of the equipment being intrusive or non-intrusive, the sites selected should provide safe working conditions. Characteristic examples are the existence of a Vehicle Restraint System (VRS) or adequate verge at the side of the motorway. In addition, there has to be a secure way to install the equipment – especially if non-intrusive – in order to prevent theft as well as deliberate or accidental destruction.

5.3.2.3. Equipment selection parameters

The main parameters, apart from the resources and safety, used for the selection of the most suitable are:

- **Ability to collect data required**

First and foremost, the equipment should fulfil the requirements for which it is set; thus the equipment should have the ability to collect the data required. The important facts about HS incursions are when and where the violations occur, the width and length of the violation as well as the speed and classification of the vehicle. Apart from collecting the aforementioned values, the measurements have to be accurate. Two main potential limitations of a technology are the influence of speed and weather.

The speed limit on motorways in the United Kingdom is 70mph (112km/h). A minimum speed limit is not generally applied *(The Highway Code, 2013)*. Speed varies around junctions, where vehicles enter or leave the motorway. Vehicles on the slip road or the inside lane accelerate or decelerate accordingly. The speed is also affected by mandatory temporary speed limits in cases of roadworks and incidents or queues. The legal speed limit for HGVs on motorways is 60mph. However, according to EU legislation, these vehicles are restricted by a speed limiter to travel at a maximum speed of 56mph *(DfT, 2014)*. Thus, the technology selected must be effective in motorway high speed conditions. In addition, if a vehicle is stationary or slow-moving, it sometimes cannot be recorded by the equipment. The same might occur with very high speeds. Vehicles that are moving too close to each other create a problem in accurately classifying them, as they are not recognised as two or more separate vehicles.

In terms of the environment, temperatures below zero are often noticed in the area, as well as frost, and, as some devices are influenced by weather conditions, the technology chosen must be suitable to work properly under the extreme conditions. Fog, snow, heavy rain, and, generally, low visibility can also sometimes influence the equipment’s performance. This also includes the detection of dark objects, which, depending on the abilities of the equipment, may be limited in comparison to other objects. In addition, when the location chosen involves a curve, there might be visibility considerations with some types of technology.

Cost

The overall cost of the use of a piece of equipment includes the following sub-categories:

Procurement: the cost of purchasing or renting the equipment, as well as all the accompanying elements (e.g. data logger, establishment of internet connection for remote data collection).

Installation: the cost that the operator (company or organisation) has to cover in order for the equipment to be fixed on the network. It includes the number of man-hours, the cost for traffic management (e.g. lane closure) if required, the possible interventions to the pavement or the existing infrastructure (gantries, light posts) that need to take place, especially if the technology is intrusive.

Operation: the cost of the energy consumed by the system and the cost for actions required during operation (e.g. manual data collection).

Maintenance: the cost (including man-hours) for inspecting and repairing, as well as the cost of any traffic management requirements.

Replacement/ Decommissioning: this cost depends on the effort required and the possible repairing that the road or the surrounding infrastructure might need, as, for example, in the case of inductive loops.

- **Installation, operation and maintenance requirements**

It is desirable to have minimum installation, operation and maintenance requirements, as this reduces, apart from the cost as mentioned above, the risk to the operatives and the disruption for the road users. For this, side-fire mounting is preferred over over-head as it is easier to install (e.g. no lane closure required) and maintain. In this context, it is generally preferable for the equipment to be non-intrusive. This means that it causes no or minimal disruption to traffic and the road infrastructure. An example of non-intrusive devices is the radar, while an example of the opposite is the magnetometer. If non-intrusive, the equipment is also portable. This is a major advantage in cases that it is necessary to collect data from several locations and there are financial constraints at the same time.

- **Overall**

Overall, it is preferred if the equipment is transferable, i.e. it is possible to move it to another location under different conditions because it provides the ability to collect data from a great variety of locations if necessary. In addition, if the equipment has been used widely in the past (for the same or other use), it means that it should be more reliable and the most common ways to deal with any problems that might appear as well as the limitations are generally known. On the contrary, the use of a more contemporary system offers a better perspective for alternative future uses.

5.3.2.4. Site selection parameters

The location characteristics are either fixed, potentially variable, slowly or constantly changing. The ones that are fixed mainly refer to the infrastructure itself and the design of the road. More specifically, these ones are the orientation of the road, curvature and slope. The ones that could potentially change over time are the type of pavement, the lighting conditions, the number and width of lanes as well as the width of the HS. The type of pavement can change in terms of surface (e.g. asphalt coating on concrete base for noise reduction around residential areas). The condition of the pavement and marking lines (including the rib-line) is slowly deteriorating and, lastly, traffic related variables (such as traffic volume and speed) are constantly fluctuating.

The characteristics of the infrastructure are collected via the as-built construction drawings for the M1A1 Link Road. These provide information for the curvature, slope and orientation of the whole network. Street lighting drawings show how each of the sections are lit (no lights, nearside only on one or both directions, central reservation only, nearside and central reservation on both directions). Traffic counting areas are always preferred as power is more easily available through access to the Clearview Traffic cabinets. During roadworks, maintenance works are taking place on the network, such as resurfacing. In these cases, it may not be possible to use a site at a particular time, for example due to a lane closure.

Visits on-site are performed to collect all the necessary information related to the DMRB restrictions, such as the Structure Free Zone. It is important to investigate the suitability of every possible location, as they might be rejected due to their inability to comply with

Highways England’s standards or safety concerns. In order to assess a location, the following aspects are considered:

- Existence of power supply, such as Clearview Intelligence Traffic cabinets
- Existence of a VRS and if so, its type and length
- Distance between the rib-line and the VRS system. If the distance is too high, the system’s efficiency might be affected.
- Distance between the VRS systems and any existent motorway structure (such as a gantry). If the distance is too low, it might not allow for the safe installation of new equipment in accordance with the standards.

5.3.2.5. Deployment of HS incursions data collection system

Based on literature review on potential solutions for an automatic HS incursions monitoring system, including a sensor based system (see ***Paper 3***), the radar is identified as the most suitable for the trial. The laser sensor’s main advantages are flexibility in terms of installation and also its low cost as a research constraint is the funding available for technology procurement. On the contrary, as a more advanced sensor, the radar sensor is expected to provide more detailed incursions data, though it is of higher cost.

NavTech Radar offers a solution using a 360° scanning radar and is identified as suitable for the trial. The equipment is usually installed at the side of the motorway and at a height monitoring a distance of around 300 metres (depending on the road geometry and line of sight). Highways England launched a trial on the M62 in cooperation with a consultant company to detect stationary vehicles on an All-Lane Running (ALR) section of Smart Motorway M62 J25-26, where the hard-shoulder has been transformed into a running lane.

For that purpose, Highways England procured 10 sensors of the same technology; however only 8 are used in their project.

Following discussions with the Project Manager of Highways England, it was agreed that a spare radar could be provided to the HS incursions project. While the cost restraint was then eliminated, the radar was selected as the technology for the HS incursions data collection trial. The second spare radar was kept by Highways England for an emergency (e.g. broken down radar) deployment. The location selected for the trial installation is on the northbound carriageway of the M1-A1 Link Road, between Junctions 46 and 47. For more details on the radar deployment procedure, see ***Appendix C***.

Radar mounting

The radar sensors are positioned to provide the optimum ‘line of sight’. In order to check what can be seen by the radar one has to stand at ground level where the radar is mounted, or ideally, at the height of the radar. Whatever is visible to a person is also visible to the radar. Street furniture, such as lamp posts, can create visual obstacles to the radar, especially further away where they appear – to the radar – to be closer together. In a straight line the radar can detect a person from 20 to 350m away, depending on the road geometry and the mounting height.

The sensor can be mounted at various heights between 2m and 8m. For the HS monitoring, a minimum height of 2m could be applied. However, for security reasons, a height of at least 3m is preferred. The higher the radar is mounted, the longer distance it covers, while at the same time the blind area underneath the radar increases. The radar sensor may be mounted on dedicated posts, or various other structures – such as walls and gantries – using brackets. It is fitted to a plate on top of the post or the bracket using nuts and bolts which allows the tilt adjustment (levelling). On the M1-A1 Link Road, there is a series of structures that could be used for the radar mounting, such as A-shape concrete gantry supports, bridges and variable message signs (VMS).

For the deployment of the radar-based system, several mounting options were considered to ensure the optimum performance of the radar and also minimisation of additional infrastructure and compliance with the Highways England Standards. Each radar sensor requires a power and data connection via an Ethernet cable. Assistance is provided by NavTech regarding the use of the radar and the software. This includes a short training course and a site visit by a NavTech engineer in order to resolve software issues, including inability to communicate with one of the radars on-site. Before proceeding with the installation, a risk assessment and method statement need to be discussed and agreed with the Management Systems Manager and the Operations Manager of the M1-A1 Link road. The possibility to remotely collect the data is discussed so that visits on-site are minimised. To setup the radar system, several additional components are required.

5.3.3. Key findings

This work package focused on the implementation of an automatic HS incursions monitoring system for data collection. A series of requirements were followed in order for the system to be deployed in a safe and efficient manner. The radar sensor-based system is installed on the northbound carriageway of the M1-A1 Link Road. The radar is mounted on a scaffold, which has been temporarily installed around a concrete gantry and all additional components of the system are installed in the cabinet existent on-site for traffic counting. The radar data are first collected in the server on-site within the radar’s software, and then sent to the remote server. The following work package includes the processing of the radar data after the remote collection and its correspondence to the conditions under which the incursions occur to estimate the risk.

5.4 HS INCURSIONS DATA COLLECTION AND ANALYSIS

5.4.1 Scope and Aim

The fourth research objective is the analysis of the HS incursion occurrences and the development of a risk model for HS incursions. This section describes the final work package which includes the data processing procedures after they are collected remotely from site and the statistical analysis of the radar data using appropriate modelling techniques, and more specifically the GLARMA model. This is to estimate the risk of HS incursions and the factors related to traffic and environmental conditions that mostly affect that risk.

5.4.2 Research Details

For the purposes of this trial, a radar sensor was installed at a straight line section of the motorway (M1-A1 Link road northbound – J46-47), following all the requirements imposed by Highways England's Standards (Design Manual for Roads and Bridges), Balfour Beatty's procedures and the supplier's instructions.

5.4.2.1 Radar sensor data

The scanning radar sensor radiates continuous transmission power and records the reflections transmitted from the objects. The raw data are collected by the radar and processed in the server connected to the sensor on-site. Plots that correspond to specific objects, such as a vehicle, are identified and then transformed into tracks. Tracks consist of a series of plots and refer to a particular object's trajectory. The radar's software records all the information related to the tracks into extractable spreadsheets.

Based on the radar's rotation speed, data are collected four times per second. Each track is assigned a unique ID number. The size of the plot is estimated and has a different value according to the distance the object is from the radar. The closer an object is to the sensor, the smaller it appears. Each object is classified based on its size; however the radar is not capable of directly distinguishing between different vehicle types. The location is recorded according to a radar-based coordinates system as well as the vehicle's direction relative to the North. Time of detection is provided in precision of seconds. The following table (Table 5.9) summarises the data received by the sensor, following the internal processing. For more information about the software installation and operation, see ***Appendix D***.

Table 5.9 Summary of the data received by the radar sensor.

Variable	Measurement Unit/ Values	Description
Track ID	integer	unique id number per track
Position	coordinates	the position of the plot in the radar-based coordinates system
Speed	metres per second	speed of the plot, calculated as the distance between two tracks divided by the time between those two samples (i.e. the radar rotation time in seconds)
Direction	rad	the primary direction of travel relative to North
Size Range	m	dimension of the plot in range (the axis towards/away from the radar)
Size Azimuth	m	dimension of the plot in azimuth (the circular axis around the radar)
Size Area	m^2	area of the plot, calculated
Strength	integer	sum of all cells (radar intensity) which exceed the threshold
Weight	integer	number of cells that are merged together to form a plot
Recorded Time	date & time	date (day/month/year) and time (hour/minute/second) of each track
Classification	vehicle/ debris/ pedestrian/ unclassified	classification of the plot based on plot size, track speed and turn rate
Classification Probability	%	classification confidence rate

- **Data sorting**

Data collected every quarter of a second are represented by a separate line in the dataset. The dataset as extracted by the software sorts all tracks in reverse chronological order. Each track is given an ID number; however this is not definitely unique. Track ID numbers are allocated in a serial manner and cannot be higher than 10,000 at which point numbering restarts. Due to the high upper limit of a track ID number, it is not expected that they are repeated within a very short period of time.

The first step is to distinguish the tracks that have been given the same automatic ID number. This is achieved by sorting all observations by track ID and timestamp. It is expected that within one track, the timestamp recordings will be consecutive, with a maximum of a second's difference, based on the time precision provided. Thus, when the absolute time difference between two consecutive observations is higher than 1 second, and lower than 59 seconds at the same time, two different tracks have been appointed the same ID. This time difference is then referring to the last observation of the n^{th} track and the first observation of the $(n+1)^{th}$ track. This cannot be equal to 59 seconds, as it would then refer to a track occurring during within two consecutive minutes (e.g. 17:15:58 – 17:16:13). All overlapping track ID numbers are corrected by creating a new track ID variable.

With all track ID numbers then being unique, a new variable is created to represent the timestamp when the track was first identified. This new variable has the same value for all the observations within the same track. This is because there are overlaps in time between consecutive tracks (e.g. 1st track: 17:15:58 – 17:16:13, 2nd track: 17:16:04 – 17:16:15) and if all tracks were sorted using the timestamp variables (hour/minute/second), the observations of the same track would no longer be grouped together.

To summarise, the tracks within a data set are ensured to have a unique ID number and are also corresponded to another unique value, which is the first time that a track was recorded. The tracks are in the end sorted using the variables in the following order: track ID and time ID. Tables 5.10 and 5.11 show how tracks that are appointed the same track ID do not correspond to the same vehicle track and need to be separated as well as how the track IDs are sorted using a new variable.

Table 5.10 Differentiation of track IDs in radar data.

Track ID as recorded	**Hour**	**Minute**	**Second**	**Time difference (seconds)**	**Splitting Track ID**
6896	…				Same Track
6896	08	45	05	-	
6896	08	45	05	00	
6896	08	45	05	00	
6896	08	45	05	00	
6896	08	45	06	***01***	
6896	08	45	06	00	
6896	08	45	06	00	
6896	08	45	06	00	
6896	…				
6897	…				Same Track
6897	17	15	58	-	
6897	17	15	58	00	
6897	17	15	59	***01***	
6897	17	15	59	00	
6897	17	15	59	00	
6897	17	15	59	00	
6897	17	16	00	***-59***	
6897	17	16	00	00	
6897	17	16	00	00	
6897	17	16	00	00	
6897	…				
6898	…				Track #1
6898	20	05	25	-	
6898	20	05	25	00	
6898	20	05	26	00	
6898	20	05	26	00	
6898	07	32	47	***21***	Track #2
6898	07	32	47	00	
6898	07	32	47	00	
6898	07	32	47	00	
6898	07	32	48	***01***	
6898	…				

Table 5.11 Radar data sorting according to unique track IDs.

Track ID	Hour	Min	Sec	Time of first recording		Track ID	Hour	Min	Sec	Time of first recording
6896	***09***	***16***	***47***	***09:16:47***		***6896***	***09***	***16***	***47***	***09:16:47***
6896	09	16	47	09:16:47		6896	09	16	47	09:16:47
6896	09	16	47	09:16:47		6896	09	16	47	09:16:47
6896	09	16	47	09:16:47		6896	09	16	47	09:16:47
6896	09	16	48	09:16:47		6896	09	16	48	09:16:47
6896	09	16	48	09:16:47		6896	09	16	48	09:16:47
6896	09	16	48	09:16:47		6896	09	16	48	09:16:47
6896	09	16	48	09:16:47		6896	09	16	48	09:16:47
6897	***09***	***16***	***48***	***09:16:48***		6896	09	16	49	09:16:47
6897	09	16	48	09:16:48		6896	09	16	49	09:16:47
6897	09	16	48	09:16:48		6896	09	16	49	09:16:47
6897	09	16	48	09:16:48		6896	09	16	49	09:16:47
6896	09	16	49	09:16:47		6896	09	16	50	09:16:47
6896	09	16	49	09:16:47		6896	09	16	50	09:16:47
6896	09	16	49	09:16:47		6896	09	16	50	09:16:47
6896	09	16	49	09:16:47		6896	09	16	50	09:16:47
6897	09	16	49	09:16:48		6896	09	16	51	09:16:47
6897	09	16	49	09:16:48		6896	09	16	51	09:16:47
6897	09	16	49	09:16:48		***6897***	***09***	***16***	***48***	***09:16:48***
6897	09	16	49	09:16:48		6897	09	16	48	09:16:48
6896	09	16	50	09:16:47		6897	09	16	48	09:16:48
6896	09	16	50	09:16:47		6897	09	16	48	09:16:48
6896	09	16	50	09:16:47		6897	09	16	49	09:16:48
6896	09	16	50	09:16:47		6897	09	16	49	09:16:48
6897	09	16	50	09:16:48		6897	09	16	49	09:16:48
6897	09	16	50	09:16:48		6897	09	16	49	09:16:48
36897	09	16	50	09:16:48		6897	09	16	50	09:16:48
6897	09	16	50	09:16:48		6897	09	16	50	09:16:48
6896	09	16	51	09:16:47		6897	09	16	50	09:16:48
6896	09	16	51	09:16:47		6897	09	16	50	09:16:48
6897	09	16	51	09:16:48		6897	09	16	51	09:16:48
6897	09	16	51	09:16:48		6897	09	16	51	09:16:48
6897	09	16	51	09:16:48		6897	09	16	51	09:16:48

- **Object positioning**

In order to position an object, the radar sensor estimates the centroid of the object (centre of mass) based on its merged plot, as shown in Figure 5.20. Subsequently, the positioning of the object is based on this centroid, regardless of the shape or size of the plot. The location of an object at a given time is defined using X and Y coordinates in a local coordination system, where (0,0) can be set by the user. For ease of use, the location of the radar sensor is selected as the centre of the coordinates system. The azimuth accuracy of the radar is 2°, which is expected to affect the sensor's performance in detecting incursions.

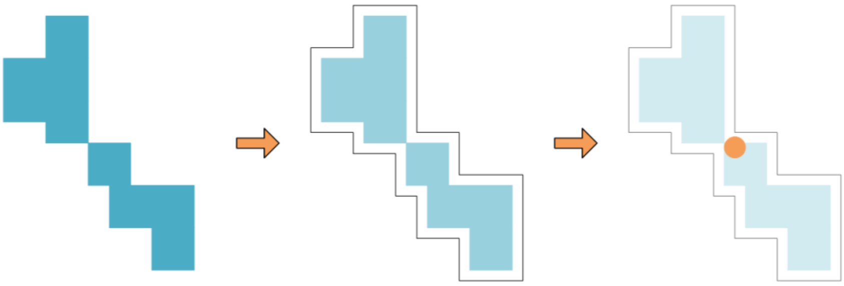


Figure 5.20 Estimation of a vehicle's centroid according to the radar's software

- **Object classification and size estimation**

The radar provides three options for the classification of an object: vehicle, debris or pedestrian. However, the radar is not able to directly differentiate between different vehicle types (e.g. car/van/HGV). It provides an estimation of the dimensions in two directions: range and azimuth. The size of the vehicle is calculated based on these two parameters (size range and size azimuth):

$$estimated\ vehicle\ size = \sqrt{(size\ range)^2 + (size\ azimuth)^2}$$

Figure 5.21 shows what the size range and size azimuth dimensions represent. These parameters are changing according to the distance from the radar where they are estimated as a plot appears to be smaller the closer it is to the sensor. According to the experience of the supplier's engineers from past projects, the vehicle size estimation is closer to the actual at a distance between 50 and 70 metres away from the radar.

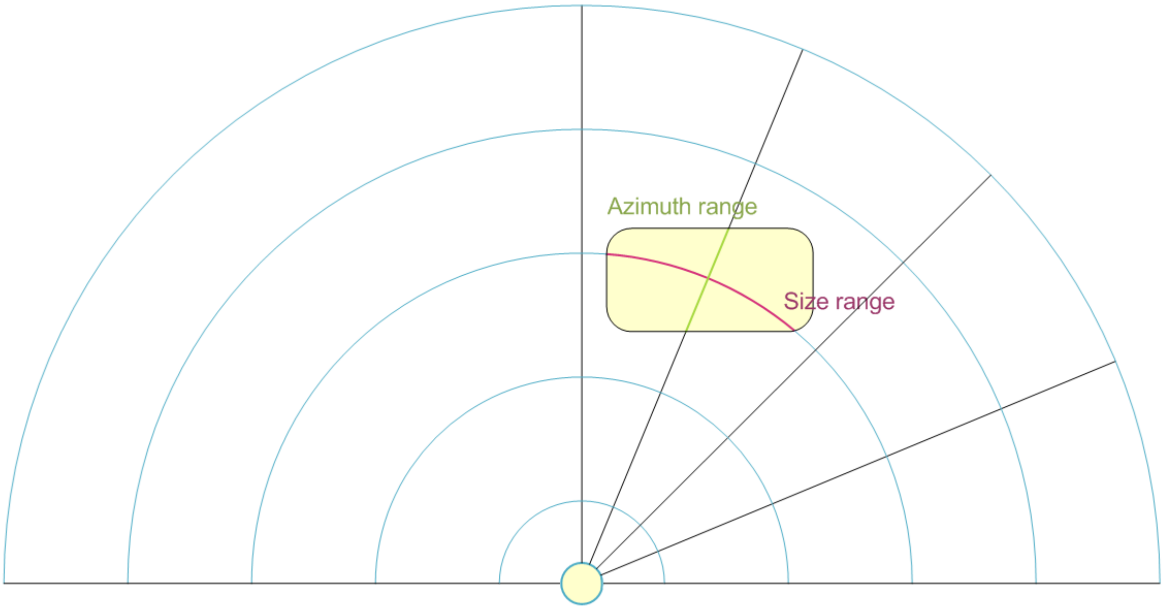


Figure 5.21 Size dimensions of a vehicle as measured by the radar

As, not all tracks include a measurement within this range (50-70m), the functions representing the relationships between the size range and the size azimuth estimations and the distance from the sensor are estimated. By plotting the size range in relation to the distance from the radar, it is noticed that the relationship of this dimension with the distance from the radar is close to linear. On the contrary, plotting the size azimuth indicates a quadratic relationship with the distance from the radar.

From these two functions, separately for range and azimuth, the estimated values for an average distance of 60 metres are calculated and then the vehicle size using the aforementioned equation. The functions are estimated for every individual track and are applied on one side of the radar range, selecting the one that has the most observations. From its estimated length, a vehicle can be classified in the general category of car or HGV. Specifically, the threshold for an HGV is set at a minimum of 5.2m, to ensure consistency with Highways England’s classification method.

- **HS incursions threshold setup**

The radar locates an object based on its centroid. After the sensor has created tracks based on the plots detected, the HS incursions thresholds are applied. In order for the radar to identify whether a vehicle track is invading the HS or not, a threshold is applied within the software (see ***Appendix D***). If the limit for a HS incursion was set as the rib line (which is the natural limit), the sensor's alarm would be raised when the centroid of the vehicle would be over the line as shown in Figure 5.22 (A). As a result, a different threshold is set, based on where a vehicle's centroid would be located when an incursion occurs. As the width of a car and an HGV are considerably different, two separate thresholds are required based on the classification, as shown in Figure 5.22 (B).

This threshold is based on the physical measurements of the distance from the radar sensor to the outer edge of the rib-line. However, the threshold needs to be altered to cover for the position of the centroid of the vehicle. The estimation of average vehicle width is further explained in the following section. The threshold line is created based on the threshold point at the radar location (perpendicular to the motorway) and the curvature as provided by the drawings of the network as constructed. The geometry-based thresholds are shown in Table 5.12. These are calculated based on physical measurements on-site in relation to the location of the radar. The radar then represents the centre of the coordination system (0,0). In order to validate the thresholds based on the geometry, incursions were performed using a test vehicle and the incursions were reviewed using the data the radar collected at the time of the tests.

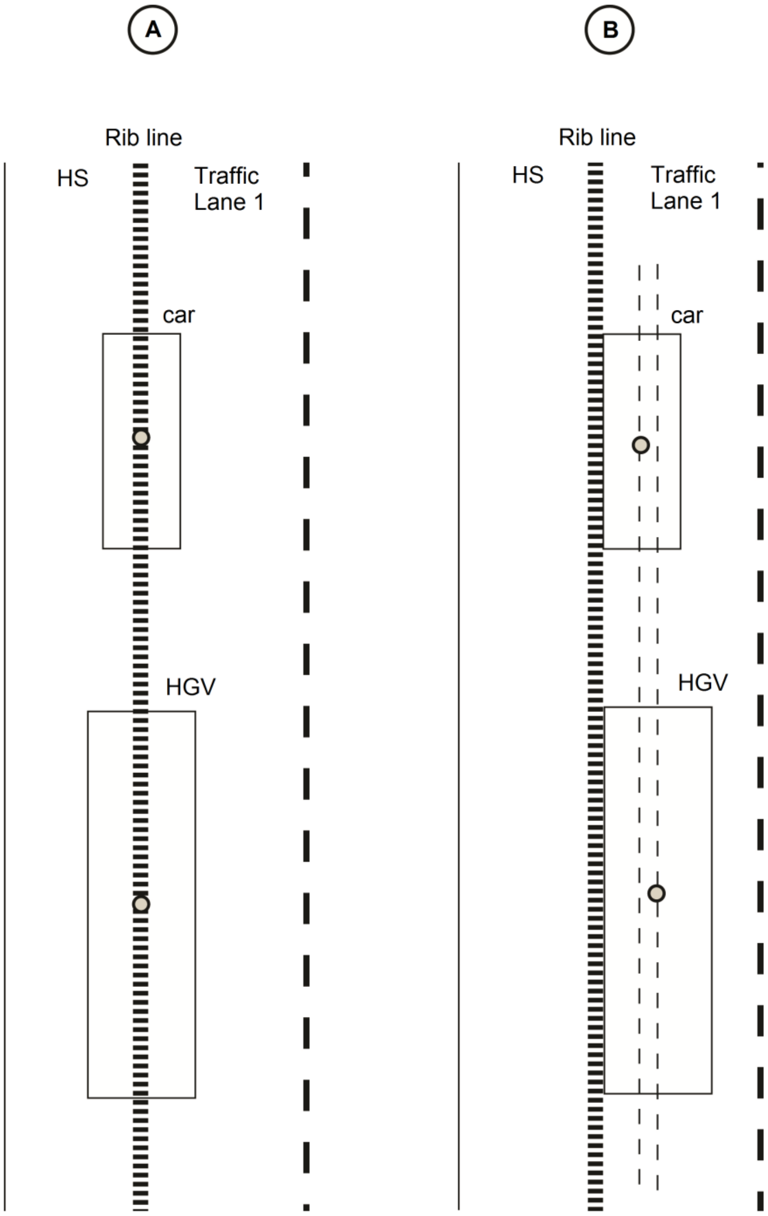


Figure 5.22 Threshold setup for HS incursions according to the vehicle classification

Table 5.12 Geometry-based thresholds for HS incursions at radar sites.

Site (Marker post/ Direction)	**Distance (mm)**			**Average vehicle width (mm)**		**Geometry-based thresholds (mm)**	
	Radar to VRS/V-channel (outside)	*VRS/V-channel (outside) to rib-line (outside)*	*Radar to rib-line (outside)*	*car*	*HGV*	*car*	*HGV*
313.4 NB	3,700	3,780	7,480	1,767	2,500	**8,363.5**	**8,730**

As the exact vertical gradient was not available at this site, this was calculated indirectly using the vertical radius information at that section of the road based on the construction designs. The highest horizontal radius on the M1-A1 Link is 10,000m (Table 5.13). This is considered approximately a straight line for the approximately 300m of the radar coverage. Figure 5.23 illustrates the blind spot underneath the radar sensor. The blind spot's range depends on the height at which the sensor has been installed; for the 3.5m height, the radius is 14,2m.

Table 5.13 Geometrical characteristics of the radar sites.

Site	**Chainage**	**Horizontal Radius (m)**	**Vertical Gradient (%)**	**Curvature** *(approx.)*	**Slope** *(approx.)*	**Orientation (relative to the North)**
313.4 NB	13,230	10,000	–1.00	straight	downhill	73°

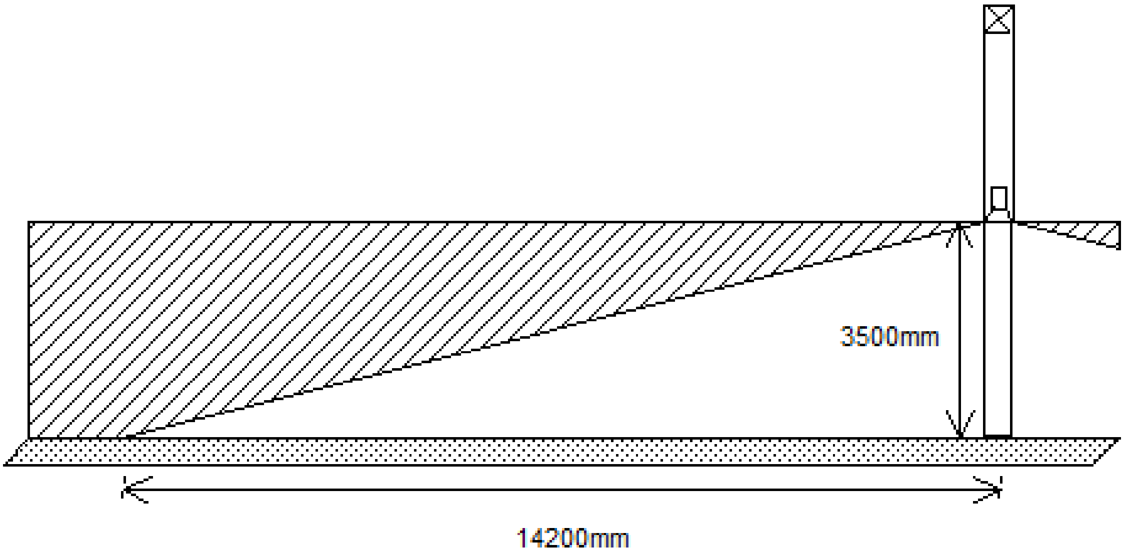


Figure 5.23 Radar sensor's blind spot for the installation on the M1-A1 Link Road

- **Estimation of average vehicle width**

In order to setup the HS incursion thresholds according to the vehicle type, vehicle data are collected from DfT, and more specifically the Vehicle Licensing Statistics collection *(DfT, 2015)*. Two datasets are used, one for cars and another for HGVs. In the first dataset, the number of licensed cars by the top 20 models at the end of 2015 is provided. The total number of the top 20 represents the 82.452% of all cars in the GB at the end of 2015 (Table 5.14). The width of each model is determined based on their latest version according to the manufacturer. The weighted average is calculated to estimate a ‘typical’ car width.

Since the area of study is in Yorkshire, an additional vehicle dataset (licensed cars by make, by region, GB from 2009 and UK from 2015) is used to compare the most popular makes between Yorkshire and the whole GB. This dataset does not provide details on specific models; however it is observed that the percentages of the makes of the top 20 most popular models are around the same levels in Yorkshire and GB (Table 5.15).

The equivalent data for HGVs have a high percentage of missing model data; however, they provide general make data. Due to the missing data, it is not possible to follow the same approach as used for cars. Based on the two most popular HGV manufacturers (DAF and Mercedes), the most common HGV width is 2,500mm, thus this is the value used as an average dimension for HGVs. A sensitivity analysis is not deemed necessary as the standard deviation of the vehicle width is low. More specifically, the average vehicle width for the different make models is 1,763mm and the standard deviation 69.3mm.

Table 5.14 Car models by popularity in GB at the end of 2015 and corresponding width dimensions.

Make Model	Number of cars (thousands)	Width of latest model (mm)
Ford Fiesta	2,871.6	1,722
Ford Focus	2,865.9	1,823
Vauxhall Corsa	2,335.9	1,746
Vauxhall Astra	2,087.8	1,809
Volkswagen Golf	2,004.5	1,790
BMW 3 Series	1,271.0	1,811
Volkswagen Polo	1,230.0	1,682
Renault Clio	1,104.6	1,732
Toyota Yaris	878.2	1,695
Ford Mondeo	866.9	1,852

Vauxhall Zafira	864.8	1,884
Honda Civic	805.0	1,770
Nissan Micra	794.9	1,665
Mercedes C Class	783.8	1,810
Audi A3	749.5	1,785
Peugeot 206	725.5	1,652
Mini Cooper	693.4	1,727
Ford Ka	686.5	1,658
Renault Megane	673.2	1,814
Audi A4	649.0	1,842
Sum	24,941.9	**-**
Total number of cars in GB at the end of 2015	30,250.3	-
Percentage of 'Top 20' models over the total number of cars	82.45%	-
Weighted average car width	**-**	**1,767**

Table 5.15 Car makes by popularity in Yorkshire and comparison with GB.

Make	Percentage of make in Yorkshire (%)	Percentage of make in GB (%)	Difference between Yorkshire and GB (%)
Ford	13.9	14.4	97.0
Vauxhall	12.9	11.6	106.9
Volkswagen	8.1	8.6	97.3
Peugeot	5.4	5.5	98.6
BMW	4.4	5.1	88.6
Toyota	5.2	4.8	112.4
Audi	4.4	4.5	98.7
Nissan	3.8	4.4	85.4
Renault	4.3	4.3	96.3
Mercedes	3.2	4.0	83.1
Honda	3.1	3.5	92.6
Mini Cooper	1.9	1.9	99.5
Sum	70.6	72.3	-
Average	-	-	**96.4**
Std Deviation	-	-	**8.3**

- **Tracking corrections**

This section describes further techniques followed to correct the extracted HS incursions data.

The following errors were noticed while investigating the tracks data at a microscopic level.

Correlation of unrelated objects

Firstly, it was noticed that the radar sensor may correlate objects that are, in reality, unrelated. As a result, two different objects appear as one track. The criterion applied for splitting the tracks that should not have been merged while tracking is based on the sudden change of speed that cannot be attributed to acceleration/deceleration. In some cases, it is noted that the speed of one track is relatively stable for its first part, then suddenly changes, and becomes stable again. It is expected that a natural vehicle’s movement would not involve such sudden changes, even at high acceleration/deceleration. When this speed change is noticed in the data, a track is split into two.

Failure to correlate related tracks

On the other side, it is also possible for the sensor to fail to correlate two tracks that belong to the same vehicle. The criterion applied for this tracking issue is related to the vehicle’s positioning. The time interval between the end of one track and the start of the next one is examined. Based on the average speed of the first track, the potential positioning of this vehicle is calculated in the given time interval. If that potential position is matching the starting position of the following track, it is assumed that these two tracks are referring to the same vehicle. This is more likely to happen due to the blind spot underneath the radar sensor, where a track is lost and may not be correlated to the same vehicle when that reappears after the blind spot.

5.4.2.2 Traffic-related data

Clearview Intelligence is a consultant company providing solutions for traffic monitoring, subcontracted by Balfour Beatty. They install, maintain and operate the inductive loops on the M1-A1 Link and conduct the traffic counting and classification on behalf of Connect Roads. There is no direct payment of ‘Tolls’ by road users on the M1-A1 Link Road; rather ‘Shadow Toll’ payments are made to the Concession Company by Highways England. These are calculated on the number of vehicle-kilometres travelled on the M1-A1 Link Road *(Highways England, 2012)*. There are nine traffic counting locations covering the M1-A1 Link Road as well as part of the M62 and the A1(M) (Table 5.16). Clearview Intelligence collect loop data which are stored and processed in the counter on-site before being wirelessly sent on a daily basis to the company’s remote servers.

Table 5.16 Traffic Counting Sites on the M1-A1 Link Road.

Direction	Motorway	Traffic Counter	Junctions	Marker Post
Northbound	M62	1A	28 – 29	113.7
	M62–M1 Link	2A	-	116.4
	M1	3A	42 – 43	302.1
	M1–A1 Link	4A	-	303.9
	M1–A1	5A	44 – 45	306.2
	M1–A1	6A	45 – 46	310.0
	M1–A1	7A	46 – 47	313.4
	M1–A1	8A	47 – 48	318.4
	A1(M)	9A	-	56.8
Southbound	M62	1B	28	113.7
	M1–M62 Link	2B	-	300.1
	M1–A1	3B	43 –42	304.8
	M1–A1 Link	4B	-	303.9
	M1–A1	5B	48 – 47	306.1
	M1–A1	6B	47 – 46	310.0
	M1–A1	7B	46 – 45	313.4
	M1–A1	8B	45 – 44	318.4
	A1(M)	9B	-	56.8

The loops collect vehicle-by-vehicle data which are aggregated into hourly data in the counter on-site. Table 5.17 summarises the information provided by the traffic counters. Every three months, Clearview Intelligence conducts data verification, using footage from the cameras installed on-site for this particular purpose, to ensure the high data accuracy. Details on the exact lane are also provided, including the HS, along with the head and gap from the leading vehicle, and also the vehicle speed. The length of the vehicle is provided in centimetres, however this is used for classification in the further processing. An HGV is defined as a vehicle longer than 5,200cm.

Table 5.17 Traffic data information collected by Clearview Intelligence's inductive loops on the M1-A1 Link Road.

Traffic Information	Measurement Unit/ Values	Description
ID	index	Unique vehicle identity number
Date	day/month/year	Date of traffic data collection
Time	hour/minute	Hours and Minutes of vehicle presence
	second	Seconds of vehicle presence
	hundredths of second	Hundredths of seconds of vehicle presence rounded to the nearest hundred
Lane	1, 2 etc.	Lane of vehicle presence (HS: Lane 1, Traffic Lane 1: Lane 2 etc.)
Direction	1 or 2	Direction of vehicle (Northbound/Eastbound: 1, Southbound/Westbound: 2)
Head	metres (max value: 99.9)	Distance between the front of a vehicle and the front of the leading vehicle
Gap	metres (max value: 99.9)	Distance between the front of a vehicle and the end of the leading vehicle
Speed	kilometres per hour	Speed of a vehicle
Length	centimetres	Length of a vehicle which is used for later classification

Based on the initial traffic data available, new variables are created to examine their potential impact on the HS incursion risk. Since the research focus is not the whole carriageway, but a particular lane (traffic lane 1), it is investigated whether the relationship between the traffic conditions on traffic lanes 1 and 2 may be significant. The traffic and speed difference between these lanes may affect driving behaviour on traffic lane 1, while traffic lane 3 is not expected to have such an impact.

Table 5.18 Traffic-related variables considered in the statistical models.

Traffic Information		Motorway Sector	Time Interval	Measurement Unit
Category	Variable			
Traffic Flow	traffic flow	traffic lanes 1 and 2	hourly	# of vehicles/ hour
	traffic flow difference	between traffic lanes 1 and 2	hourly	# of vehicles/ hour
Speed	average speed	traffic lanes 1 and 2	hourly	miles per hour
	speed variance	within traffic lanes 1 and 2	hourly	miles per hour
	speed difference	between traffic lanes 1 and 2	hourly	miles per hour
Vehicle Composition	vehicle composition	traffic lanes 1 and 2	hourly	% of vehicles
	vehicle composition difference	traffic lanes 1 and 2	hourly	% of vehicles

5.4.2.3 Environment-related data

As part of the contract with the Highways England, Balfour Beatty is responsible for the winter maintenance at the M1-A1 Link Road. This includes salt spreading when icy conditions are forecast and snow clearage. As weather stations were not already installed very close to the area, two ice prediction stations were installed and are maintained by Vaisala, whose service include providing environmental measurements, especially weather-related. The weather data collected by the stations are sent to the MetOffice, the UK’s National Meteorological Service, who develop the forecasts and inform the Operator via Vaisala. The winter maintenance period is between October and end of April; however the stations are constantly collecting data which are accessible throughout the year. Each station provides information on the temperature, precipitation, wind and pavement environmental condition (Table 5.19).

Further explanation for the values of each categorical variable, as well as a map highlighting the locations of the two stations – Hook Moor and River Aire – are found in ***Appendix E***. Since the radar is located closer to Hook Moor weather station, the data used in the analysis are taken from this particular one. The MetOffice can also provide data from five additional stations around the M1-A1 Link road (see ***Appendix E***). Each station can provide different data (Table 5.20); however, none of the above stations are closer to the radar location than Hook Moor station, hence their data are not utilised in the research.

Table 5.19 Weather data collected by Vaisala's stations.

Weather Variable		**Type**	**Measurement Unit**	**Description**
Temperature	Surface	S	°C	Temperature on the surface of the pavement
	Air	A	°C	Temperature recorded usually 2m above the ground
	Dew point	A	°C	Temperature moisture would condense out of the atmosphere, should the air or object cool to this point. The higher the dew point, the higher the moisture content
	Depth	U	°C	Temperature 10cm below the ground surface
Precipitation	Rain state	A	textual expression	Precipitation intensity detected
	Rain intensity	A	mm/h	Intensity of any current precipitation
	Total precipitation in the past 24h	A	mm	Total amount of precipitation recorded since 06:00UTC each day
Wind	Wind speed	A	mph	10 minute average (prior to reading)
	Wind direction	A	16 point compass	10 minute average (prior to reading)
	Wind gust	A	mph	10 minute maximum (prior to reading)
Pavement Condition	Surface state	S	textual description	Substances and solutions on the surface
	Level of grip	S	0.0 – 1.0	Indication of tyre traction levels. Value influenced by detection of water, ice or snow on road or runway surface
	Water layer	S	mm	Amount of water detected on the surface
	Ice layer	S	mm	Amount of ice detected on the surface
	Snow layer	S	mm	Amount of snow detected on the surface
Atmosphere	Relative humidity	A	%	Percentage of the moisture content of the air
General	Alarm Status	S	textual description	Textual warnings of imminent hazardous conditions based on measurements from other parameters

A: Atmospheric, S: Surface, U: Underground

Table 5.20 Weather data availability from MetOffice weather stations.

Met Office Weather Station	**Weather data**		
	Temperature	Precipitation	Wind
Bingley, No2	✓	✓	✓
Bradford	✓	✓	
Bramham	✓	✓	✓
Dishforth Airfield	✓	✓	✓
Ryhill	✓	✓	
Linton-on-Ouse	✓	✓	✓

A new variable is also created: relative wind direction. This variable refers to the wind direction in relation to the orientation of the motorway section being monitored. As shown in Table 5.13, the orientation of the particular motorway section is 73^{o}, which – based on a 16 point compass system – approximately corresponds to ENE-WSW direction. As discussed in the literature review, especially HGVs' movement is expected to be affected by the wind. The relative wind direction is defined as an ordinal categorical variable. The value is 0 when the wind direction is the same as the orientation of the motorway section, while the more perpendicular the wind becomes to that orientation, the higher the variable's absolute value. Values from -4 to 4 and depending on the side wind's direction and is positive when the side wind blows 'towards' the HS.

The weather data reports, as provided by Vaisala, are aggregated every 10 minutes and for this study are transformed into 15 minute interval. The treatment for continuous and discrete variables is different. For *continuous* variables, from the initial values for 0, 10, 20, 30, 40 and 50 minutes of an hour, the average values of consecutive pairs are taken (i.e. 5, 15, 25, 35, 45 and 55 minutes). The values for the 15 minute interval are the initial for 0 and 30 minutes and the average for 15 and 45 minutes. For *discrete* variables (surface state, rain state, wind direction and alarm state), the value at 10 minutes is taken for the 0-15 minutes period, the value at 20 minutes for the 15-30 minutes period, the value at 40 minutes for the 30-45 minutes period and, lastly, the value at 50 minutes for the 45-0 minutes period. Then the average between 0 and 15 minutes is used the duration between 0-15 etc.

Another environment-related variable created is related to darkness. This is a dummy variable receiving the value 1 during hours of darkness, and 0 during hours of daylight. It is calculated based on the exact hours of sunrise and sunset for the period of data collection. However, the hours of darkness are defined, according to the *Highway Code (2017)* as the period between

30 minutes after sunset and 30 minutes before sunrise; hence this is how the ‘darkness’ variable is also defined.

5.4.2.4 HS incursions radar data analysis

Based on the thresholds as described in ***§5.4.2.1***, only the tracks that represent a HS incursion are extracted from the dataset. Data of a month (June 2016) are aggregated in 15 minutes intervals. Each 15-minute period is corresponded to the traffic and weather conditions. Table 5.21 provides the summary statistics for the key dependent and independent variables.

Table 5.21 Summary statistics for key dependent and independent variables.

Variable	**Mean**	**Std. Dev.**	**Min**	**Max**
Number of HS incursions (15 min)	20.60	19.00	0	148
Track size	23.66	9.33	10	86
Points over threshold	13.00	6.76	4	57
Speed (meters per sec)	24.00	2.24	5.84	34.01
Estimated size (m)	8.27	1.30	4.98	13.01
Vehicle class	.91	.28	0	1
Temperature surface (°C)	14.47	4.81	3.15	28.75
Temperature air (°C)	11.77	3.37	1.43	20.20
Rain state	3.96	.22	1	4
Rain intensity (mm/h)	.03	.34	0	13
Wind speed (mph)	4.51	2.56	.55	15.23
Relative wind direction	2.25	0.20	0	4
Wind gust (mph)	11.45	5.60	1.53	32.23
Surface state	1.25	.56	0	3
Level of grip	.81	.025	.46	.82
Water layer (mm)	.01	.024	0	.47
Ice layer (mm)	.000052	.000848	0	.03
Snow layer (mm)	.000099	.001177	0	.03
Relative humidity (%)	69.73	14.77	32.50	91.00
Darkness	.28	.45	0	1
Flow MC – all vehicles (hour)	1518.70	1162.56	15	4760
Flow MC – other vehicles (hour)	1254.75	1030.11	7	4310
Flow MC – HGVs (hour)	263.95	221.46	8	865
Flow lane 1 – all vehicles (hour)	591.42	330.16	9	1267
Flow lane 1 – other vehicles (hour)	403.09	267.12	5	1077
Flow lane 1 – HGVs (hour)	188.33	138.19	4	518
Flow lane 2 – all vehicles (hour)	634.17	511.52	4	1817
Flow lane 2 – other vehicles (hour)	572.78	467.91	1	1750
Flow lane 2 – HGVs (hour)	61.39	68.70	0	350
Flow difference lane 1 & lane 2 – all vehicles	-42.75	213.86	-963	286
Flow difference lane 1 & lane 2 – other vehicles	-169.69	259.40	-783	210

Flow difference lane 1 & lane 2 – HGVs	126.93	77.47	-320	282
Classification MC (%)	24.42	18.00	3.99	80.53
Classification lane 1 (%)	36.14	20.46	6.54	86.87
Classification lane 2 (%)	10.83	8.70	0	75
Classification – difference lane 1 & lane 2 (%)	25.31	13.79	-30.56	72.93
# of vehicles with speed below 40mph MC (hour)	.46	7.91	0	199
# of vehicles with speed between 40mph and 70mph MC (hour)	3.51	58.71	0	1466
# of vehicles with speed between 70mph and 100mph MC (hour)	322.78	255.29	10	1867
# of vehicles with speed over 100mph MC (hour)	1191.94	940.68	5	3819
Average speed MC (hour)	111.00	5.59	87.30	121.70
Std. dev. of speed MC (hour)	15.41	1.50	11.80	30.70
Speed difference between lane 1 and lane 2	16.58	3.07	-13.50	32.10

In the methodology, the severity of an incursion is defined from its maximum width and length. However, an accurate way of obtaining this information based on the radar data was not identified. Thus, only frequency (likelihood) of incursions is measured on which the risk estimation will be based. Even though the radar range is up to 500 metres, for accuracy purposes, only data from up to 150 metres range are utilised.

It is noted that the radar is detecting a high number of HS incursions, which, based on the results of the 2nd work package, is known to be highly inflated. This is a systematic error of the radar, as it follows traffic patterns, and it may be explained either based on the sensitivity of the sensor on the line of sight, or the sensitivity of the incursion rule applied (see Appendix). On one hand, radar performance may have been affected by the visibility due to road infrastructure (especially road signage). On the other hand, the inflated number of HS may have been caused by oversensitivity of the incursion rule used in the software. The multiple alerts recorded were filtered using the HS threshold however the number was still inflated.

To account for this error a calibration procedure is required. To calibrate the radar data, footage from the verification cameras of Clearview Intelligence is manually reviewed to collect ground truth data. An empirical relationship between the HS incursions detected by the ground truth and the radar data for the corresponding period is developed and the radar data is transformed based on that relationship. Different functional forms are tested and the final functional relationship provides the highest goodness-of-fit statistic, R^2, i.e. $R^2=0.77$. This is shown below:

$$ground\ truth\ data = -0.000274 * radar\ data^2 + 0.067362 * radar\ data$$

This functional form is used to correct the detection of HS incursions by the radar. Figures 5.24 and 5.25 show the time-series of the number of incursions per 15 minutes for a period of a month, in which there are some missing observations due to radar faults (e.g. memory incapacity).

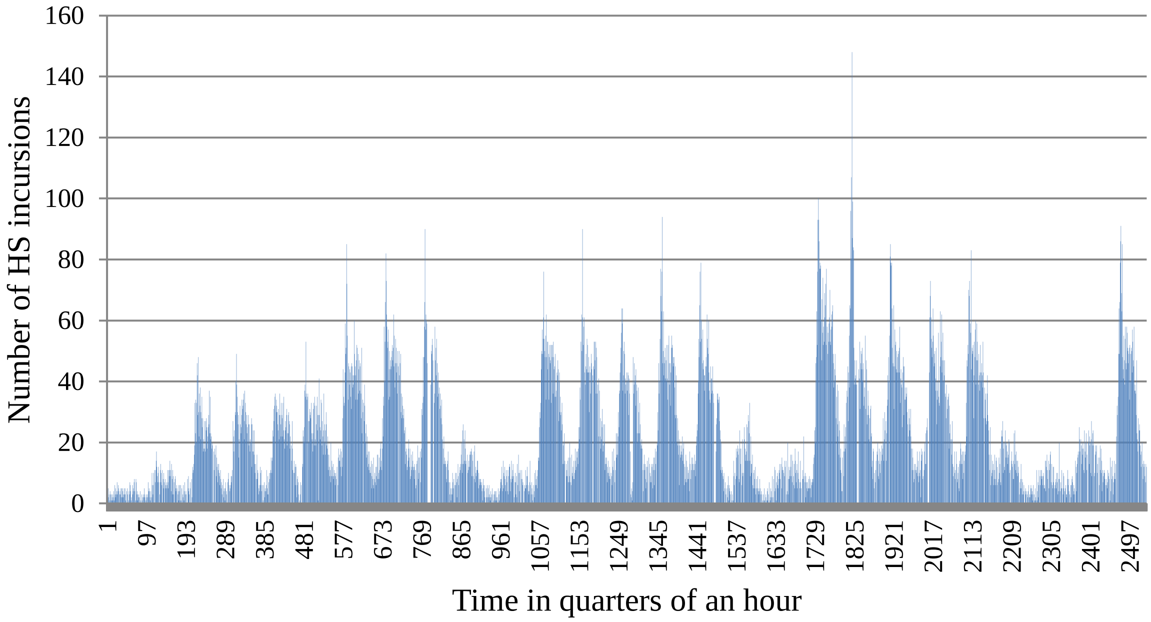


Figure 5.24 HS incursions per 15 minutes before radar data transformation

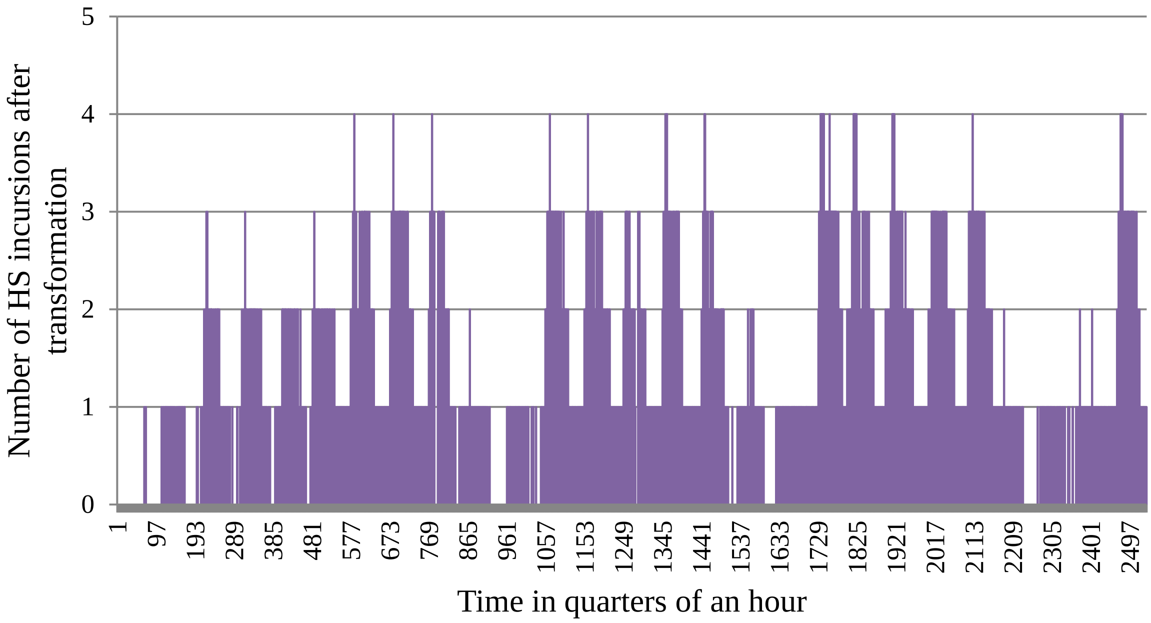


Figure 5.25 HS incursions per 15 minutes after radar data transformation

GLARMA model description

There are N successive observations $\{Y_t: t = 1, 2, \dots\dots, N\}$ of a series that represents the HS incursions count at a particular location at a temporal unit t (in this study 15 minutes). The GLARMA model assumes the conditional distribution of Y_t given the past $\mathcal{F}_{t-1}$ to be Poisson with mean μ_t *(Davis et al., 2003)*:

$$Y_t|\mathcal{F}_{t-1} \sim Poisson(\mu_t)$$

It is further assumed that the state process $\log(\mu_t)$ follows a linear model in the explanatory variables with residuals with the following moving average structure:

$$\log(\mu_t) = W_t = \alpha + \sum_{i=1}^{r} \beta_i X_{ti} + \vartheta_t + Z_t$$

In the above equation, μ_t is the expected number of HS incursion counts; α is the intercept; X_t is a r-dimensional vector of regressors at time *t*; $\vartheta_t \sim Gamma(\frac{1}{k}, k)$ in which k is the over-dispersion parameter (a higher k value corresponds to higher dispersion – for Poisson model *k*=0); Z_t accounts for serial dependence in the HS incursion counts using the linear combinations of past predictive residuals$(e_t) = \frac{Y_t - \mu_t}{\mu_t}$:

$$Z_t = \sum_{j=1}^{\infty} \gamma_j e_{t-j}$$

where $\gamma_i$are the weights for the infinite moving average.

$\{Z_t\}$ is derived using the autoregressive moving average (ARMA)-like recursions i.e. ARMA(*p*,*q*) process with noise given by $\{e_t\}$ as shown below:

$$Z_t = \sum_{i=1}^{p} \phi_i \left(Z_{t-i} + e_{t-i}\right) + \sum_{i=1}^{q} \theta_i \, e_{t-i}$$

in which p and q are the orders of Autoregressive polimonial ϕ and Moving Average polimonial θ respectively. The $\{Z_t\}$ can be thought of as the best linear predictor of a stationary invertible ARMA process. The GLARMA R-package is used for the estimation of the models.

Results of statistical modelling

HS incursions data (15-minute interval) before and after the transformation are employed in the GLARMA models development. This is to see whether there is any significant difference between the models. The results are presented in Table 5.22. The explanatory variables with a high correlation (such as traffic flow on lane 1 and darkness) were not simultaneously included in the models. The same applies to the traffic variables generated from the original traffic data and refer to lanes 1 and 2 of the carriageway; these, as expected, have a high correlation with the corresponding variables that refer to the whole MC.

Pearson residuals were used and fitting was achieved through the maximum likelihood optimised by the Newton Raphson (NR) iterative method, while the Fisher scoring iterative method was also tested. Various combinations of autoregressive (AR) and moving average (MA) lags up to 96 (representing a day) were tested in order to identify the most suitable model for the data. The final GLARMA models are selected based on the statistically significant AR and MA lags as well as the AIC (Akaike Information Criterion) value, which operates as a relative measure between models; the model with the lowest AIC value is preferable. For the original data, the GLARMA NB model was applied, while for the transformed data, the GLARMA Poisson model was found more suitable. The explanatory variables included in the final models are significant at a 90% confidence level (critical t-value is 1.671).

Table 5.22 GLARMA model estimation results for HS incursion data before and after transformation.

Dependent variable: HS incursions per 15 minutes	**GLARMA after data transformation**		**GLARMA before data transformation**	
	coefficient	*t-statistic*	*coefficient*	*t-statistic*
temperature	0.0523	3.865	0.044	5.286
humidity	0.0084	3.028	0.011	5.758
flow lane 1 – all vehicles	0.0022	9.740	0.00195	22.583
classification lane 1	0.0376	15.044	0.038	23.746
flow difference lane 1 & lane 2 – all vehicles	0.0004	1.716	-	-
Speed average carriageway	0.0213	2.107	0.0337	5.410
intercept	-6.3521	-5.285	-4.795	-6.250
Autoregressive (AR) term at lag 1	0.2755	7.810	0.1913	12.828
Autoregressive (AR) term at lag 96	0.0822	2.670	0.0620	4.006
Moving average (MA) term at lag 2	0.1414	4.817	0.1238	8.842
Estimation methods				
Residuals	Pearson		Pearson	
Model fit	Poisson		NR	
Log-likelihood at convergence	-2727.403		-9078.769	
Akaike Information Criterion (AIC)	5474.806		18175.54	
Likelihood Ratio Test (LRT)	133.2	<2e-16	348.8	<2e-16
Wald test	124.2	<2e-16	312.4	<2e-16
Data source	*Transformed*		*Original*	
Number of observations	2538		2538	

The results show several explanatory variables being significant on both models. In terms of the set of statistically significant factors, the findings are quite similar expect the variable – flow difference between lane 1 and lane 2 for all vehicles – that is marginally significant in the model related to after data transformation. Both AR and MA terms also exhibit similar patterns. There are, however, some differences in terms of the values of the coefficients. In relation to the traffic conditions, the total flow of lane 1 (nearside lane, next to the HS), as well the classification of the vehicles on lane 1 are significant on both models. The classification variable suggests that when the percentage of HGVs on a lane is higher, the probability for a HS incursion is also higher. As stated, the difference in flow between lane 1 and lane 2 is a significant variable in the model using the data after the transformation, having a positive coefficient, suggesting that a risk of a HS incursion drops when the flow is similar on lanes 1 and 2, possibly because the flow is generally smoother. The average speed of the whole carriageway also appears to affect the risk, increasing the number of HS incursions when the speed is higher.

Regarding the weather related variables, the temperature of the air is significant with a positive coefficient, suggesting that the higher the temperature, the higher the risk for a HS incursion is. This is in line with the outcome of the first research objective which examined the number of motorway accidents over time and suggested that the temperature has a positive effect on the likelihood of MC accidents. However, the temperature was not found significant for the HS accidents. Another common variable on both models was humidity. This is also suggested to have a positive effect on HS incursion likelihood. Humidity has also been linked to the accident risk in the HS accident model of the first work package. Other weather related variables, such as wind direction and grip level, which could be expected to be significant based on the factors affecting motorway accidents did not appear to have a significant effect on the HS incursions likelihood based on these models.

5.4.3 Key findings

This work package provided information on the factors affecting the likelihood of HS incursions, based on the data collected by the radar sensor and after these where transformed using ground truth data. Both traffic and weather-related variables are significant for the occurrence of HS incursions. These models can be used for the near real-time estimation of HS incursion risk given the conditions on the motorway are known. This is information particularly useful to the Operator, who can then organise the activities on-site according to when and where the risk is expected to be minimised based on the prediction model.

6. FINDINGS & IMPLICATIONS

This final Chapter summarises the key findings of the EngD, the contribution of the research to existing theory and practice, as well as the implications to the industrial sponsor and the wider industry. It concludes with recommendations for future work and a critical evaluation of the research.

6.1. KEY FINDINGS OF THE RESEARCH

The overarching aim of the EngD was to explore and quantify the risks of HS incursions for vehicles that stop on the HS. The HS of a motorway is normally used in cases of emergency; however, road workers perform operation and maintenance activities whilst their vehicles are parked there, which imposes a risk for them to be struck by an oncoming vehicle that swerves off the adjacent main carriageway lane. The project was organised in four work packages, each to achieve a research objective. The objectives, which are discussed in more detail in Chapter 2, are summarised as follows:

- To investigate the motorway accidents occurring on the HS (severity and frequency).
- To explore the various factors affecting the occurrence of HS incursions based on survey data.
- To identify and employ a suitable method which can be used anywhere on a motorway network to collect data related to HS incursions.
- To analyse the occurrences of HS incursions and develop risk models

1st research objective

The first work package included a literature review on motorway safety and the factors affecting the accident severity and likelihood. It was identified that no previous work had been conducted specifically into motorway HS safety. However, there is an extent of research related to motorway accidents in general and their contributory factors. Based on Heinrich's safety triangle theory (discussed in Chapter 4), it was assumed that the occurrences of fatal accidents on the HS in dependent on the occurrences of HS incursions. Thus, it is expected that the factors affecting HS accidents also affect HS incursions.

The severity and frequency of motorway accidents in GB were investigated (separately for HS and MC). It was identified that both MC and HS accident severity increases when an HGV is involved, while decreases during hours of daylight and when roadworks are present. Fatigue is also significant for both accident groups, having a negative effect on severity. MC accidents' severity appeared to increase during non-peak hours, when the average travelling speed is higher, the pavement surface is dry and weather is fair or foggy. These results generally suggest that the perception of risk by road users is lower when the conditions on the motorway appear to be 'safer'. The likelihood of MC accidents is increasing according to the proportion of vehicle miles travelled by HGVs on motorways and also under rainy or sunny weather conditions. On the other hand, HS accidents' likelihood is reduced by the increased presence of MSAs on motorways.

2nd research objective

To achieve the second research objective, a survey was conducted to collect HS incursions information on motorways from direct observers. The severity of incursions was found to be higher during dry pavement conditions, night-time hours and when the visibility was good, which is consistent with the findings of the first work package on risk perception by the road users. The incursions frequency was higher when the pavement was wet and lower when the visibility was good and during daytime hours.

3rd research objective

In order to develop an automatic system for HS incursion monitoring and data collection, a further literature review was conducted and a series of potential systems was identified. The main parameters that affect the process of installing new technology on the motorway network were then explored, which were mainly related to Balfour Beatty’s procedures as well as Highways England’s. This provided an insight into the various aspects related to safety and efficiency of installation and operation, minimisation of cost and the effectiveness of the system in relation to its purpose that need to be taken into consideration when deploying a new system, especially when the Operator has not worked with something similar before. A radar-based system was selected as the most suitable for the trial and was installed on the network in a novel way, using scaffolding to avoid evasive intrusion into a piece of existing road infrastructure. All the additional components of the system were installed on-site and a remote connection was also set up to minimise the visits required for on-site for data collection and other activities.

4th research objective

The final work package of this research focused on the collection and processing of the HS incursions data collected from the radar sensor system, and also the additional data required to explain under which conditions the incursions mostly occur. It was identified that the radar sensor detected more incursions than expected (based on the outcome of the 2nd work package), thus calibration was required, based on ground truth data. Also, further steps to improve data quality were related to the tracking errors identified with close investigation, the repeated track ID numbers and the vehicle positioning.

The research revealed that over a section of 150m an incursion occurs every 5 minutes, which highlights the hazards of stopping on the HS. The HS incursions data were aggregated in 15 minute intervals and then linked to the traffic and environmental conditions present at the same time and GLARMA modelling was applied. The model was developed for both the original data and the transformed, based on the ground truth data, to discover any potential differences. Most of the significant variables were common in both models – temperature, humidity, % of HGVs, and average speed on the carriageway which all increase the likelihood of an incursion – however, the variable related to the flow difference between lanes 1 and 2 was only significant in the model utilising the transformed data. The time-series related terms (AR and MA) were similar in both cases. These models may be used to predict the HS incursion occurrences at any point given the traffic and weather conditions are known, as discussed further in the following sections.

6.2. CONTRIBUTION TO EXISTING THEORY AND PRACTICE

This EngD project highlighted a gap in the existing literature, as motorway HS accidents have not been investigated in the past separately to the main traffic lanes. In the first work package, it was emphasised that MC and HS accident severity and frequency are not affected by the same factors. In addition, fatigue was investigated as an independent factor, even though in the initial STATS19 accident records, it is incorporated in the 'impairment or distraction' group of contributory factors. It was found that fatigue is the third most common contributory factor for the HS accidents, while it did not appear within the five most common ones for MC accidents. In addition to this, the effect of MSAs was explored and found to be significant for the HS accidents, supporting that the increase of MSAs across the UK is related to the decrease of HS accident occurrences.

Further to the HS accident investigation, a new risk indicator for the operatives and the public that stop on the HS was introduced and measured (HS incursion). No prior knowledge existed on the conditions under which HS incursions usually occur. For this research, a system was especially deployed to monitor them. Even though there are a variety of technologies used for traffic counting and/or vehicle detection, a solution that could be directly applied to the objectives of this research was not identified. A well-known solution (radar-based) was adopted; however its application was unique for the supplier as well and the system needed to be adapted to meet the project's requirements and collect primary data from the motorway site.

A variety of statistical models were applied during this research to investigate HS accidents and HS incursions. Discrete choice and time-series modelling had not been used for these purposes before and were successfully developed to analyse HS accident and incursion occurrences. The techniques were tested for their suitability for the particular datasets and were selected accordingly.

6.3. IMPLICATIONS/IMPACT ON THE SPONSOR AND THE WIDER INDUSTRY

Road operatives generally, and particularly in highways, have been recognised as a high risk working group in the UK and internationally. Balfour Beatty has identified risk of operatives on the HS as key. However, there was little knowledge on how this risk can be mitigated and the operatives protected. The introduction of HS incursions as a risk indicator provides the opportunity to investigate these events, and by taking measures to avoid them, reduce the injuries as well. This project produced models that correlate the likelihood of incursions to the traffic and environmental conditions under which these occur. Thus, it is possible to quantify the risk and forecast when this will be minimised according to the explanatory variables proposed. For example, the models state that when the percentage of HGVs on lane 1 is high, there is also a higher risk for HS incursions. Thus, it is generally possible, using available traffic and environment-related data, to forecast the risk at a particular location at any time.

As part of the EngD project, the wider industry was engaged. Highways contractors, including Balfour Beatty, along with Highways England, organise regional Road Safety Forums, in which health and safety issues arising in highways operations are discussed. Several forums across England were attended during the project period to raise the issue of road workers' safety while performing their tasks on the live motorway and discuss the current practices of the industry. It was identified that generally the industry, even though it identifies the issue from experience, has not explored any potential solutions. Reactive risk mitigation measures have been trialled such as the traffic cones that warn the operatives when struck by an oncoming vehicle alerting them to the possible danger. However, this research provides a better understanding of the HS incursions issue which allows for proactive mitigation measures.

The HS incursion risk model may be incorporated in a management system to deploy road workers on the network. The likelihood of incursions has been linked to the traffic and weather conditions on the motorway. By inputting the predictions of these conditions in the risk model, it is possible to also predict the risk for a HS incursion at a particular motorway section at any time. According to the level of risk acceptance, which may be decided by the operator, this model is a tool that may allow the operatives to be deployed on the network in the safest manner. For instance, when the risk of HS incursions within a section and period of time is unacceptable, the works on site may be delayed until the risk is predicted to be tolerable.

On another angle, the radar supplier explored a new application for their product and expressed interest in developing some of the radar features (and especially the azimuth resolution) further so that it performs better in similar applications in the future. In addition, as part of the radar data processing, a method to estimate the size of a vehicle more accurately and individually for every track was developed. This is something that the radar supplier has not applied before within their software and expressed interest in adopting.

6.4. CRITICAL EVALUATION OF THE RESEARCH AND RECOMMENDATIONS FOR FUTURE RESEARCH

The main challenge of this research has been the identification and deployment of a suitable system for HS incursion monitoring and data collection. The reason for this was that there was no system that had been used before for this or a similar application. Hence, an innovative application was developed on an existing sensor. However, providing that the system was new to the sponsoring company as well, there were many uncertainties to be investigated during deployment, such as the mounting method for the radar sensor, as the off-the-shelf solutions were not appropriate.

The radar sensor deployed, even though it is of high performance compared to other systems, was trialled in a novel application. This highlighted the weakness of the sensor to perform well at its usual distance (300-350m), which in this study needed to be reduced to ensure more reasonable accuracy levels (150m). Due to the sensor’s accuracy, it was also not possible to collect detailed information on the incursions’ characteristics (e.g. width).

For future research, alternative technologies that have been recently significantly developed (such as video image processing) may be considered. This could also lead to more detailed incursions data. The data in this research were calibrated using CCTV-based ground truth data to account for the systematic error of over-counting. This exercise should be replicated whenever incursions data are collected at a different location. In the next research steps, the data will also be validated using the calibrated radar data and CCTV-based ground truth data (another dataset to the one used for the calibration). Further collection of additional data from multiple sites is recommended in order to develop models using a greater sample, and investigate whether additional explanatory variables such as curvature of the motorway, slope, lane width etc are significant and need to be included. An expansion of the data collection may also provide insight of particular locations that the risk of HS incursions is particularly high, hence information to the public in order to prevent use of the HS may be provided. The behavioural aspect (e.g. distraction) may also be investigated in the future, to identify potential correlation with the likelihood of incursions.

This project revealed the extent of interdependencies among stakeholders (e.g. DBFO, Operator, Highways England, technology suppliers etc.) to perform a trial on the motorway. Providing the relationships that have developed through this research, it would be recommended that innovative ideas are openly discussed amongst the different teams to identify new opportunities for technology development on the motorway network, especially since this is a rapidly growing area of research.

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APPENDIX A: BALFOUR BEATTY CONSTRUCTION WORKFORCE’S TASKS

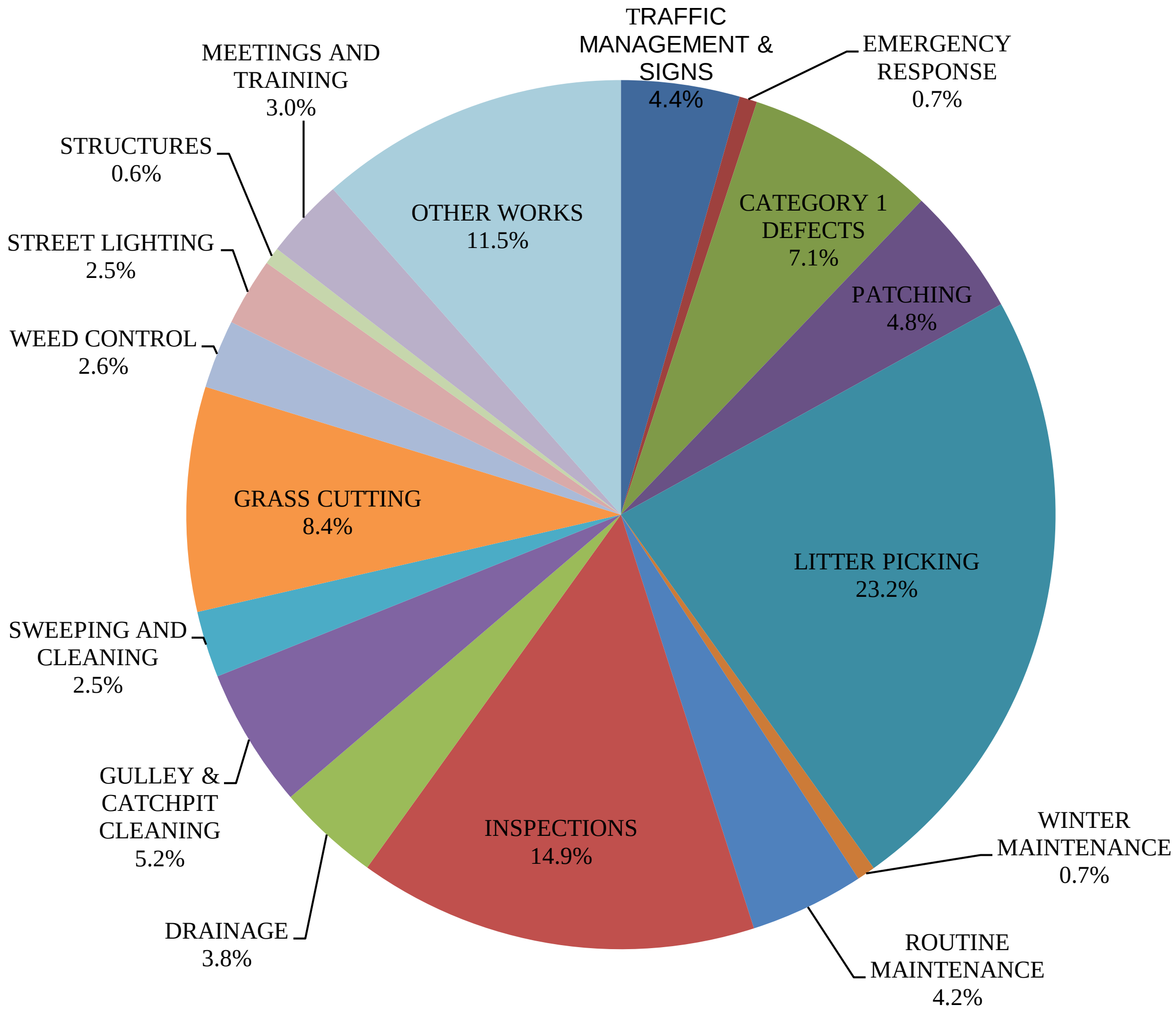

Figure A1 Balfour Beatty Construction workforce’s task distribution for the financial year 2014 – 2015

APPENDIX B: HIGHWAYS ENGLAND'S REQUIREMENTS FOR NEW EQUIPMENT INSTALLATION

1. STRUCTURAL REVIEW

This is a review of an individual structure (such as a bridge or gantry) or group of structures within the highway structures stock, to establish or confirm the validity of the latest Assessment (or original design, if there has been no subsequent Assessment) and identify any need for further assessment. The Assessment includes inspections and determination of load carrying capacity of a structure or part of a structure in terms of either full Authorised Weight loading or specified gross vehicle weights, or other applied vehicle loading (including impact). A Structural Review is only carried out if the need arises. Events that might trigger it include changes in condition (detected by the inspection programme), operational load carrying requirements and Assessment standards (DMRB BD 101/11, 2011).

2. TECHNICAL APPROVAL

The submission of Proposals for agreement by the Technical Approval Authority and the subsequent provision and acceptance of certificates confirming that the design, assessment, specification or construction works complies with the agreed Approval in Principle and design/assessment and specification certificates as appropriate. The Proposals are placed in one of four Categories (0, 1, 2 or 3) according to several criteria that depend on the size and complexity of the Structure. Category 0 refers to the less complex Structure.

3. VEHICLE RESTRAINT SYSTEM (VRS) LENGTH OF NEED

The VRS Length of Need is the total minimum length of full height, full containment VRS stipulated by the Designer, as a result of the Road Restraints Risk Assessment Process (RRRAP), as being required in advance of, alongside, and after a hazard/hazards to protect the hazard/hazards. The length over which various VRS reach full containment may vary and will need to be checked with the manufacturer. The overall length of safety barrier required will be the Length of Need plus the additional lengths that are declared by the manufacturer to be required before and after the Length of Need to ensure that the safety barrier attains full containment. The safety barrier provided to protect a single hazard, or group thereof, must be a continuous length that may or may not be made from one type of product (DMRB TD 19/06, 2006).

Table B1 Minimum lengths of safety barrier on motorways according to the containment level. *(Source: DMRB TD 19/06, 2006)*

Safety Barrier Containment Level	**Minimum Lengths of Safety Barrier**	
	In advance of hazard	Beyond hazard
Normal	30m	7.5m
Higher	30m	10.5m
Very High	45m	18m

Therefore, it has to be ensured that the installation of any equipment is not affecting the performance of the VRS. Thus, the equipment cannot be installed within the minimum lengths, which would mean that the VRS would not be able to function properly in case of an impact. Figure 4.1 shows how the minimum lengths apply.

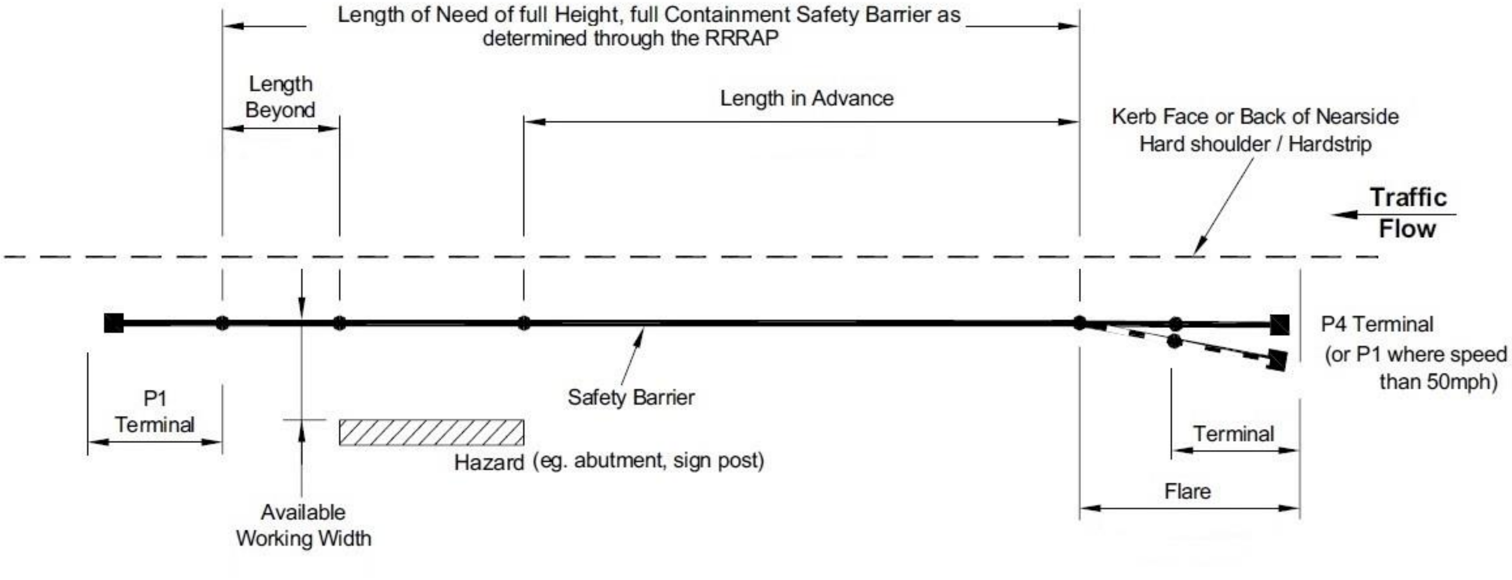

Figure B1 Verge Safety Barrier Layout Adjacent to Hazards *(Source: DMRB TD 19/06, 2006)*

4. WORKING WIDTH

The working width is the maximum lateral distance between any part of the barrier on the undeformed traffic side and the maximum dynamic position of any part of the barrier. If the vehicle body deforms around the road VRS so that the latter cannot be used for the purpose of measuring the working width, the maximum lateral position of any part of the vehicle shall be taken as an alternative.

The working width need to remain clear from any installations so the VRS can perform properly. Objects should not normally be placed within the Working Width as this will affect the performance of the safety barrier. The objects are likely to be impacted and may also have a detrimental effect on the vehicle hitting it and will increase the risk of injury to its occupants. Road furniture and equipment must not be positioned in front of a new or existing VRS and, in general, it should not be placed immediately in advance of nor within the available Working Width unless the road furniture or equipment has been designed to be passively safe and, if hit, will not be displaced into the adjacent carriageway or give rise to a secondary event.

The Working Width (W) in the TD19/06 Standard (DMRB TD19/06, 2006) is based on the BS EN 1317-2:1998 definition. This definition assumes:

W = width of the VRS + VRS maximum dynamic lateral deflection + vehicle intrusion beyond the VRS (also known as overhang).

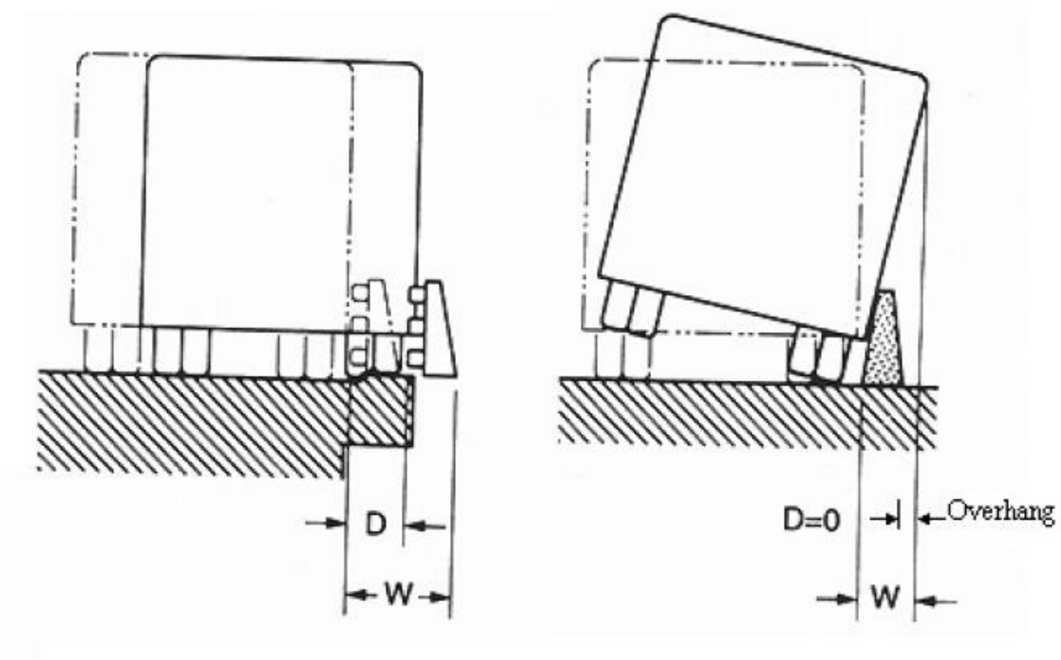

Figure B2 Dynamic Deflection (D), Working Width (W) and Overhang in case of an impact with a deformable (left) and a rigid (right) Vehicle Restraint System *(Source DMRB TD19/06, 2006)*

When a (Very) High Containment or rigid VRS is hit by an HGV or other tall vehicle, there is a tendency for the vehicle to roll and intrude into the area behind the VRS. This normally occurs to a lesser degree with Normal Containment deformable safety barriers which deflect more. Thus, a check must be carried out to ensure that there is sufficient clearance between the protected hazard (in this case the equipment installed) and the VRS, in order for the hazard to not be hit by a vehicle intruding over the VRS (DMRB TD 19/06, 2006).

5. STRUCTURE FREE ZONE (SFZ)

The *Cross-Sections and Headrooms* (DMRB TD27/05, 2005) Standard sets out the dimensional requirements for the highway cross-sections for all-purpose and motorway trunk roads, both at and away from structures. It also gives requirements for headroom at structures. This document was followed in order to select the sites in terms of feasibility as well as the method of mounting the equipment. If it were not possible to achieve the installation of the equipment while meeting the full Standards, a Departure would be required.

The Structure Free Zone (SFZ) is a buffer zone adjacent to the Paved Width (the surface of the road cross-section that comprises the carriageway, hard-shoulder and hard strips) and beneath a Structure that reduces the risk of errant vehicle impacts by providing an appropriate value of Headroom (the minimum distance between the surface of the highway cross-section and the deflected structure –including any temporary or permanent attachments – measured at right angles to the surface of the cross-section). Errant vehicles may leave the road pavement leading to a risk of collision with components of the structure.

6. VEHICLE RESTRAINT SYSTEM (VRS) SET-BACK

Obstructions immediately adjacent to the edge of the paved carriageway result in drivers reducing speed and positioning their vehicles away from the obstruction. The purpose of the set-back is to provide a lateral distance between the VRS and the carriageway which reduces the effect of the safety barrier on driver behaviour and driver shyness. Any proposals for departures or relaxations must consider in verges with a hard-shoulder the effects on the ability of occupants of parked vehicles to leave via the nearside doors and the possibility of increased risk due to parking closer to live traffic. Reducing set-back exacerbate the likelihood of impacts and side-swipes between vehicles in adjacent lanes and reduced space for maintenance vehicles and operatives (DMRB TD27/05, 2005)

APPENDIX C: RADAR DEPLOYMENT

Based on literature review on potential solutions for an automatic HS incursions monitoring system, including a laser sensor based system (see ***Paper 3***), the radar is identified as the most suitable for the trial. NavTech Radar offers a solution using a 360° scanning radar (Figures 5.10, 5.11). The equipment is installed at the side of the motorway and at a height monitoring a distance of around 300 metres (depending on the geometry of the road) and can provide much more details. Highways England has launched a trial on the M62 in cooperation with Atkins to detect stationary vehicles on All-Lane Running (ALR) section of Smart Motorway M62 J25-26.

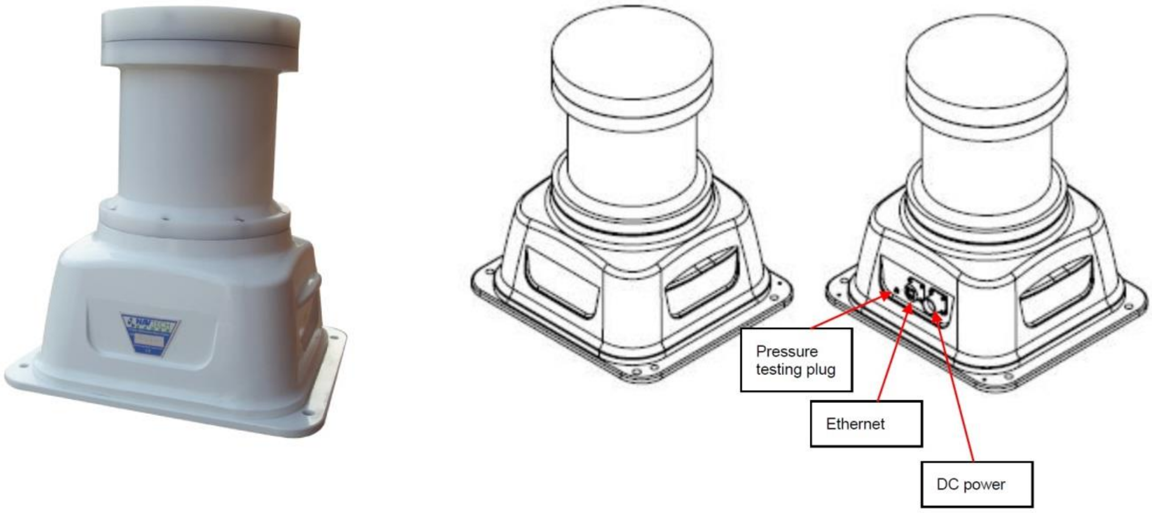

Figure C1 NavTech Radar TS Series – Isometric views

For that purpose, 10 radars were bought from NavTech; however only 8 are actually used for the trial. Following discussions with the Project Manager of Highways England that one of the two spare radars would be provided for the HS incursions project. The other spare radar was kept by Highways England for an emergency (e.g. broken down radar) deployment. The location selected for the trial installation is on the northbound carriageway of the M1-A1 Link Road, between Junctions 46 and 47.

Radar mounting

The radar sensors are positioned to provide the optimum ‘line of sight’. In order to check what can be seen by the radar one has to stand at ground level where the radar is mounted, or ideally, at the height of the radar. Whatever is visible to a person is also visible to the radar. Street furniture, such as lamp posts, can create visual obstacles to the radar, especially further away where they appear – to the radar – to be closer together. In a straight line the radar can detect a person from 20 to 350m away, depending on the road geometry and the mounting height. The sensor can be mounted at various heights between 2m and 8m. For the HS monitoring, a minimum height of 2m could be applied. However, for security reasons, a height of at least 3m is preferred. The higher the radar is mounted, the longer distance it covers, while at the same time the blind area underneath the radar increases. The radar sensor may be mounted on dedicated posts, or various other structures – such as walls and gantries – using brackets. It is fitted to a plate on top of the post or the bracket using nuts and bolts which allows the tilt adjustment (levelling). On the M1-A1 Link Road, there is a series of structures that could be used for the radar mounting, such as A-shape concrete gantry supports, bridges and variable message signs (VMS).

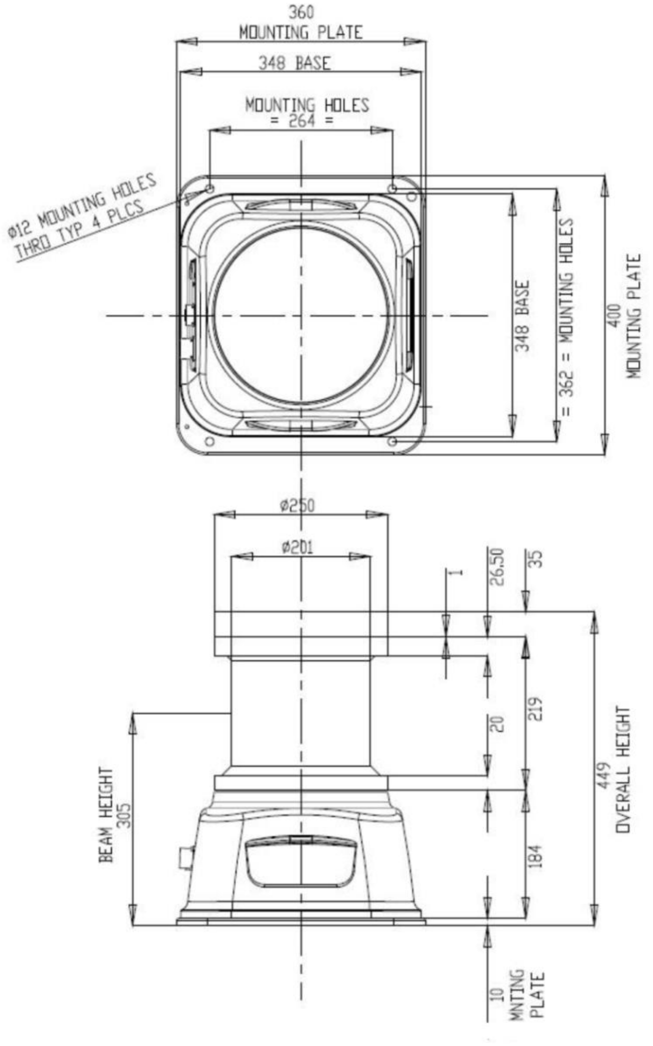

Figure C2 NavTech Radar TS Series – Dimensions

- ***Metal bracket***

A custom made metal bracket can be used along with a plate as described above. The bracket can be installed either at the side of a gantry (by drilling into the concrete) or on its horizontal beam. However, the height of the horizontal beam is normally only around 2m, slightly varying according to the location. In this case, it would be required to create an additional base of at least 1m. Because of the alteration in the load that the gantry has to carry, a Structural Review would be required for approval. The cost for the construction of a bracket is generally low, though a design from a specialised consultant is required. WSP was approached to undertake the design, however the design cost was prohibitive, particularly relative to the actual risk. The disadvantages of the metal bracket solution are, on the first case, the intrusion in the gantry (with drilling), or the large weight of the additional base structure in the second case. In addition, for the installation of a base either at the side or the horizontal beam of a gantry, traffic management is required; a lane 1 closure as a Mobile elevating work platform (MEWP) has to be used. This means higher disruption for the road users and higher cost for the installation (lane closure charges, equipment etc).

- ***Pole***

The solution of a pole was also considered, as it is one of the suggested solutions by NavTech Radar. The cost was considerably higher than the metal bracket and the installation would also require disruptive traffic management, increasing the cost further.

- ***Trailer Mast System***

A trailer mast system by Clark Mast, supplied as a loan at no cost by Highways England, was also considered. This trailer has been used before by Highways England to mount the same type of radar sensor in another project. The operational manual of the trailer provides information on how the trailer should be towed, manoeuvred and set-up, as well as how the mast should be erected, levelled and secured. Solar panels and a wind generator can be installed for power support and CCTV is also an optional addition. The dimensions of the trailer are 4.83x1.92x2.00m and the approximate weight 520kg. The extended height can reach up to 15m. Even though the trailer could operate independently power-wise, which provides more flexibility, the size of it considerably restricts the locations where it can be used safely (see ***§5.3.2.1***). In addition, the trailer would have to be transferred from a remote location to the site and back, which would increase the cost. This solution would have higher maintenance requirements as well as certifications for its safety prior to the transfer.

- ***Scaffold***

A scaffold is a temporary structure that can provide a stable base for the radar sensor. This is the solution considered the most suitable for this installation. The base plate, manufactured by Tadweld, a one-off fabrication operator, is fastened on the scaffold and the radar sensor is settled on top. To investigate the suitability of a scaffold installation for radar mounting, Complete Access, a scaffolding company approved by Balfour Beatty, was consulted. The advantage of using a scaffold for this purpose is the non-intrusiveness to the existing structures on the network, as the radar is only installed temporarily. In addition, the scaffold is installed 'around' a concrete gantry, thus the structure does not have to carry any additional weight and the scaffold can be designed and installed to accommodate individual site conditions (Figure 5.12).

For the scaffold to be installed, traffic management is required, more specifically a HS closure of a length of around 300m each side. After the scaffold is set up and the desired height is ensured (around 3.50m) using a simple distance measurement laser, the base plate is secured on top of the scaffold and then the radar is installed and levelled so it is parallel to the motorway surface. The levelling is achieved by using the nuts and bolts of the base plate. The base plate is first levelled to 0° and then the radar according to the motorway slope to ensure correct line of sight (Figure 5.13).

According to the HSE, a scaffold has to be inspected on a weekly basis. However, the scaffold installed on the M1A1 Link is not normally used for access, apart from when the radar is installed and then in emergency cases. Thus the ladder is removed and taken off-site to prevent unauthorised access. In addition, the scaffold tag that displays the inspection dates is also removed, thus it appears as the scaffold is incomplete, to also discourage any members of public or operatives to attempt access. Whenever access to the radar is necessary, for instance in case of inspection required after adverse weather conditions, the scaffold and ladder are inspected by a competent person, and the tag attached, so that access is permitted (as shown in Figure 5.12).

Figure C3 The scaffold installed on the M1-A1 Link road for the radar mounting

Figure C4 Radar’s line of sight (northbound/southbound) as installed on the M1-A1 Link Road

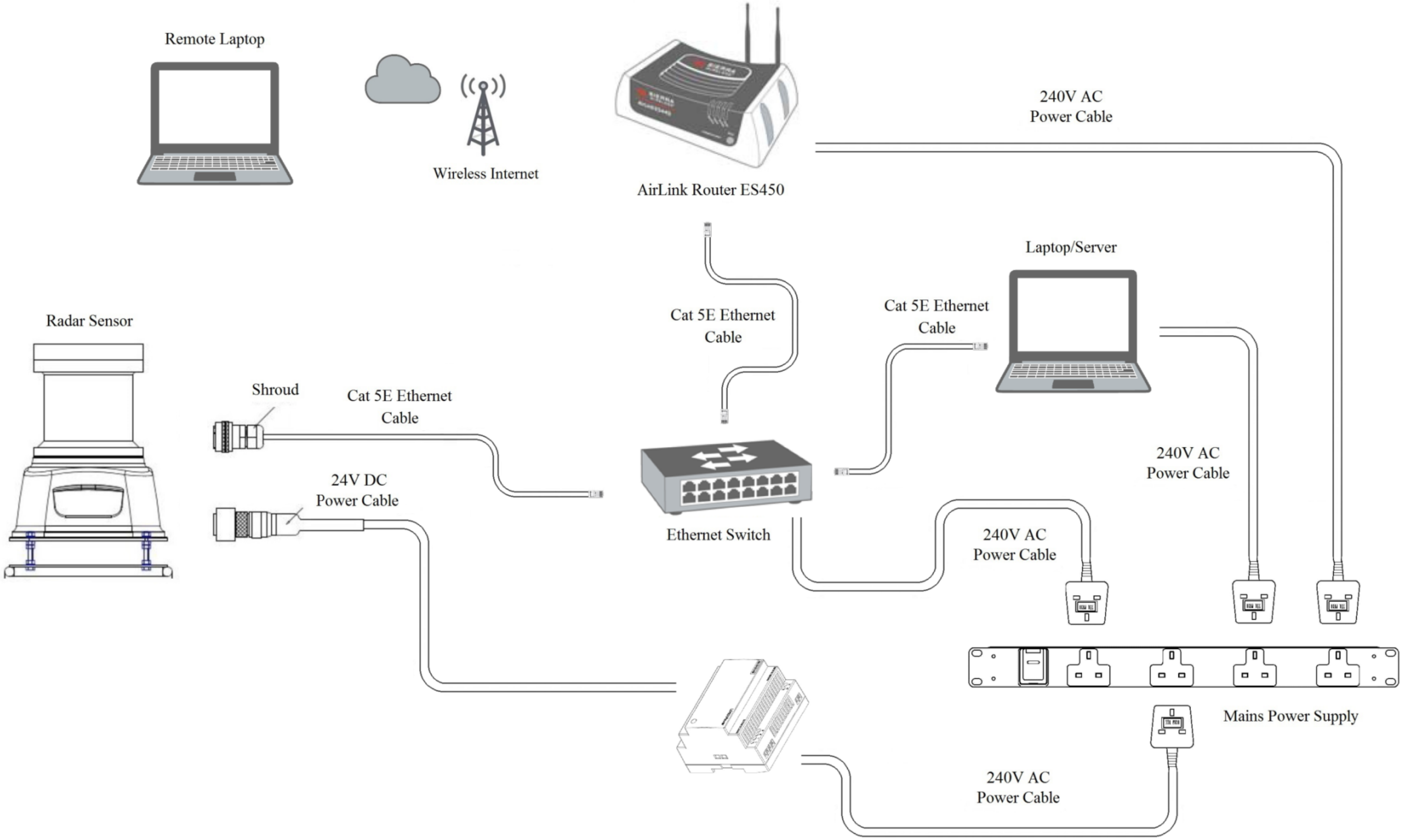

Figure C5 Connections of the radar sensor system including all components

Setup of the radar sensor-based system

Figure 5.14 shows all the connections of the radar system. Each radar sensor requires a power and data connection via an Ethernet cable (Figure 5.15). Assistance is provided by NavTech regarding the use of the radar and the software. This includes a short training course and a site visit by a NavTech engineer in order to resolve software issues, including inability to communicate with one of the radars on-site. Before proceeding with the installation, a risk assessment and method statement need to be discussed and agreed with the Management Systems Manager and the Operations Manager of the M1-A1 Link road. The possibility to remotely collect the data is discussed so that visits on-site are minimised. To setup the radar system, several additional components are required.

Figure C6 Ethernet (left) and power connection (right) of the radar sensor on the M1-A1 Link Road

- ***Power supply***

The radar sensor is working at a 24V DC voltage and is powered via the mains from a Clearview Intelligence cabinet which are at 240V AC voltage (Figure 5.16). For this, a power switch is required; the Siemens LOGO!Power switch is used (Figure 5.17). The power cable is provided with a military specification connector for the sensor connection and a bare end at the switch connection (Figure 5.15).

Figure C7 A Clearview Intelligence cabinet on the M1-A1 Link Road

Figure C8 Power switch of the radar system installed on the M1-A1 Link Road

- ***Ethernet connection***

An Ethernet cable is connected to the sensor for data transfer. A military specification shroud is supplied by NavTech to ensure a suitable environmentally protected network connection (Figure 5.15). At the other end, the Ethernet cable is connected to an Ethernet switch, which is also powered via the mains (Figure 5.18).

Figure C9 Ethernet switch of the radar system installed on the M1-A1 Link Road

- ***Laptop/Server connection***

A laptop or server is connected to the radar via the Ethernet switch (Figure 5.19). All components of NavTech Radar software are installed and running constantly on this device to process the raw radar data provided by the sensor. The laptop or server are required to have certain specifications and are selected accordingly.

- ***Router connection***

In order to have remote access to the laptop/server on-site, a router connection is set up (Figure 5.19). The SIM card for the router to set up wireless internet connection on-site is provided by Clearview Traffic. The IP addresses of all components (SIM card, router, on-site laptop/server, remote laptop) are synchronised for the system to function.

In order to connect remotely to the laptop/server on-site, a remote access software (LogMeIn) is used. A yearly account is set up which can support up to two host computers. The host computers are the ones *to* which access is required, which the client computers the ones *from* which access is achieved. There is no restriction in the number of client computers that can be used for access, as long as the software is installed and the account details available.

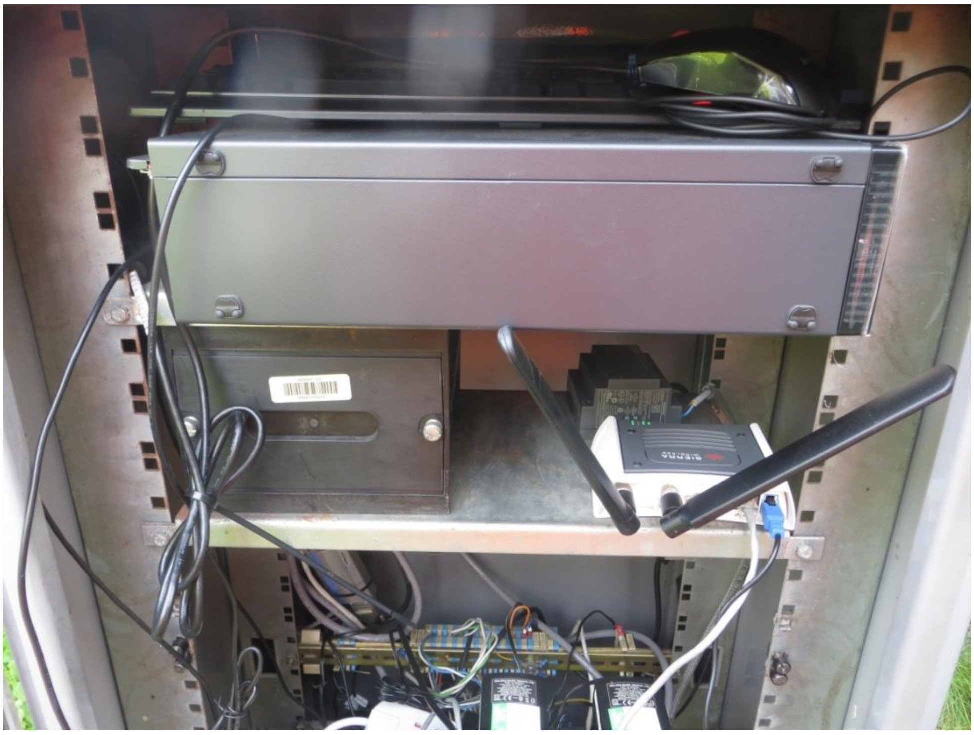

Figure C10 Server on-site (top) and router connection (bottom right) installed on the M1-A1 Link Road

APPENDIX D: RADAR CHARACTERISTICS AND SOFTWARE SETUP

The radar sensors' characteristics can be summarised as follows:

Angle Coverage: 360 degrees

Angular Resolution: 0.4 degrees

Azimuth beamwidth: 2 degrees

Elevation beamwidth: 40 degrees in the near field

Update rate: 120rpm

Maximum detection distance: 500 metres radius

NavTech Radar has developed a piece of software, called *Witness*, accompanying the sensor to continually monitor its output. After interpreting the data received, it decides when alarms should be raised according to the user's settings. In order to install the software on the laptop/server connected to the sensor, a series of prerequisites need to be met. In addition, NavTech provides specification recommendations for the computer hardware that is used to host Witness, e.g. high speed multicore processor (one processor per sensor), Windows 7 x64 Professional/Windows Server 2008 R2, 100Mbps/1Gbps Ethernet link.

Witness software consists of several components which in this trial are all installed on the same computer, as each installation includes one sensor. For the user, the visible component is the Sentinel application. Behind this, the hub of the whole system is Piccadilly, acting as the data server through which all of the other components communicate. The last module installed is Bloodhound (one per sensor), which processes the raw information from the allocated radar determines all objects within the field of view. The interpreted information is transferred to Piccadilly. Some of the components available do not have an application in this trial, thus are not installed. These are Canary (needed when a real-time alarm needs to be raised), Cyclops (needed when cameras are also incorporated in the system) and Foxhound (only for flat panel radar sensors).

The raw data goes through three levels of processing in order to generate a track, i.e. an object of interest. The processing chain is:

Raw radar data → *Processed data* → *Plots* → *Tracks*

The raw radar data first undergoes thresholding. Essentially, this is a filter which only passes reflections that meet or exceed a pre-determined amplitude. The threshold process results in processed radar data, which are a smaller dataset representing objects which exceeded a specified signal to noise ratio. Plot extraction now analyses the physical size of the processed data 'pixels' in order to (most likely) exclude very small pixels which are generated from i.e. grass, trees, water etc. If left unfiltered these would potentially lead to false alarms. Plot extraction therefore uses physical dimension values, mostly, to filter the data. These can be specified in metres, degrees or pixels. This series of processing leads to a collection of objects with sufficient amplitude and physical size to be considered an object of interest, or track.

However, there is no concept of how fast an object is travelling, or in which direction, or how many times it has been seen previously. To achieve these values several adjacent scans are analysed. Automatic track initiation serves as the final processing stage, the output of which is a track, and is configured mainly with variables such as how many times an object has been seen, the minimum and maximum speed, as well as the direction +/- a certain error margin in degrees.

The Sentinel application, as the user's interface, allows the parameters setting and real-time results as objects are tracked. A series of steps are required to configure the software according to the study's needs. These are:

For every radar sensor, the system requires a matching tracker service, therefore both are added and edited together. The tracker is a piece of software whose purpose is to convert raw data received from a single radar into track data. One scanning radar is added per site, including information such as the model type, IP address and coordinates. The parameters of the tracker can be altered to suit each situation.

- **Adding lane blocks, carriageways, lanes and sections**

Carriageways are used to represent roadways with one or more lanes travelling in the same direction. A lane block is a collection of carriageways. Normally, a lane block would contain two separate carriageways, and each carriageway he appropriate number of lanes. Each carriageway can be subdivided into sections at roughly 100 metre intervals in case defining the location where an alarm is raised is required. In this study, the lane blocks include one carriageway and are designed so that the hard-shoulder and traffic lane 1 (nearside lane) are covered.

- ***Adding a detection area and fine-tuning***

Detection areas are used to define the outer limits of where we wish to pay particular attention for each side of the road. Generally one area is used per direction of traffic flow and is allocated to a particular sensor. This allows the area of interest to be isolated from the surroundings land and the carriageway that is not monitored but could create noise if included in detecting. The area can be fine-tuned using live radar data. As the carriageway becomes further from the radar sensor, any given object will produce a wider trace due to the beamwidth of the sensor. Therefore, it is necessary to widen the carriageway area (and subsequent lane widths) as it stretches away further from the sensor.

- **Creating new tracking parameters**

Tracking parameters determine how the radar data conditioned by the tracker are used to produce valid information about tracked objects (vehicles). These are a set of filters that determine how objects seen within that area are converted into valid targets to which logical rules can be applied. To be actively used, the tracking parameters need to be linked to the area(s) that are to be monitored within one or more trackers. Before a tracker can provide useful information to the system, it needs to be linked to at least one detection area plus a set of tracking parameters. A single set of tracking parameters can be applied to one or more detection areas. The parameters include turn rate, direction (angle relative to North) and direction error (the maximum possible variation in degrees from the stated direction of travel (plus and minus this value).

- **Creating clutter maps**

A clutter map is a record of the static objects (e.g. safety barrier, lamp posts) within range of a radar sensor. Clutter maps are created and used as reference points for radar sensors and their trackers so that they can better concentrate on objects that are moving. A clutter map is created for each radar sensor. The clutter map can be periodically updated to take account objects that have moved in the interim. Clutter map time dictates how much of the radar data coming in contributes towards movement detection. Its unit is data per revolution of the radar (i.e. per 1 scan). For a value of 0.8, this means 20% of the data from the scan goes to form the clutter (background radar picture). Therefore 80% is analysed for movement. The higher the number, the more the data is analysed for movement, and the more sensitive it is to movement. Recommended setting is between 0.8 and 0.95.

- **Defining rules**

Once the data have been processed through the tracker channels and shaped by the tracking parameters, the resulting interpreted output is fed into the Rules Engine. This is where decisions are made according to a series of rule definitions that separate potential incidents from normal traffic behaviour. Rules consist of basic conditions which can be combined if necessary or adjusted to achieve the desired outcome. There are several types of rules, such as approach rules (object being closer than x metres to a particular location and moving towards it), queue rules (an end of a traffic queue being in the radar's area), speed rules (object travelling slower or faster than x mph) and tail gating rules (object being closer than x metres to the object ahead of it).

The radars are programmed to be triggered when a vehicle is crossing the rib-line of the hard-shoulder. Hence, the rules used in this study are:

- Lane change: An object changed between carriageway lanes with the radar area
- Area movement: An object is inside the radar area

The objects can be categorised as 'friendly', a 'warning' or a 'threat'; however in this study all vehicles are characterised as a 'threat'. The Break Allowance is the number of times a rule has to be broken before raising an alarm. This number is wanted small to detect quickly but not too small to create too many false alarms.

APPENDIX E: WEATHER DATA

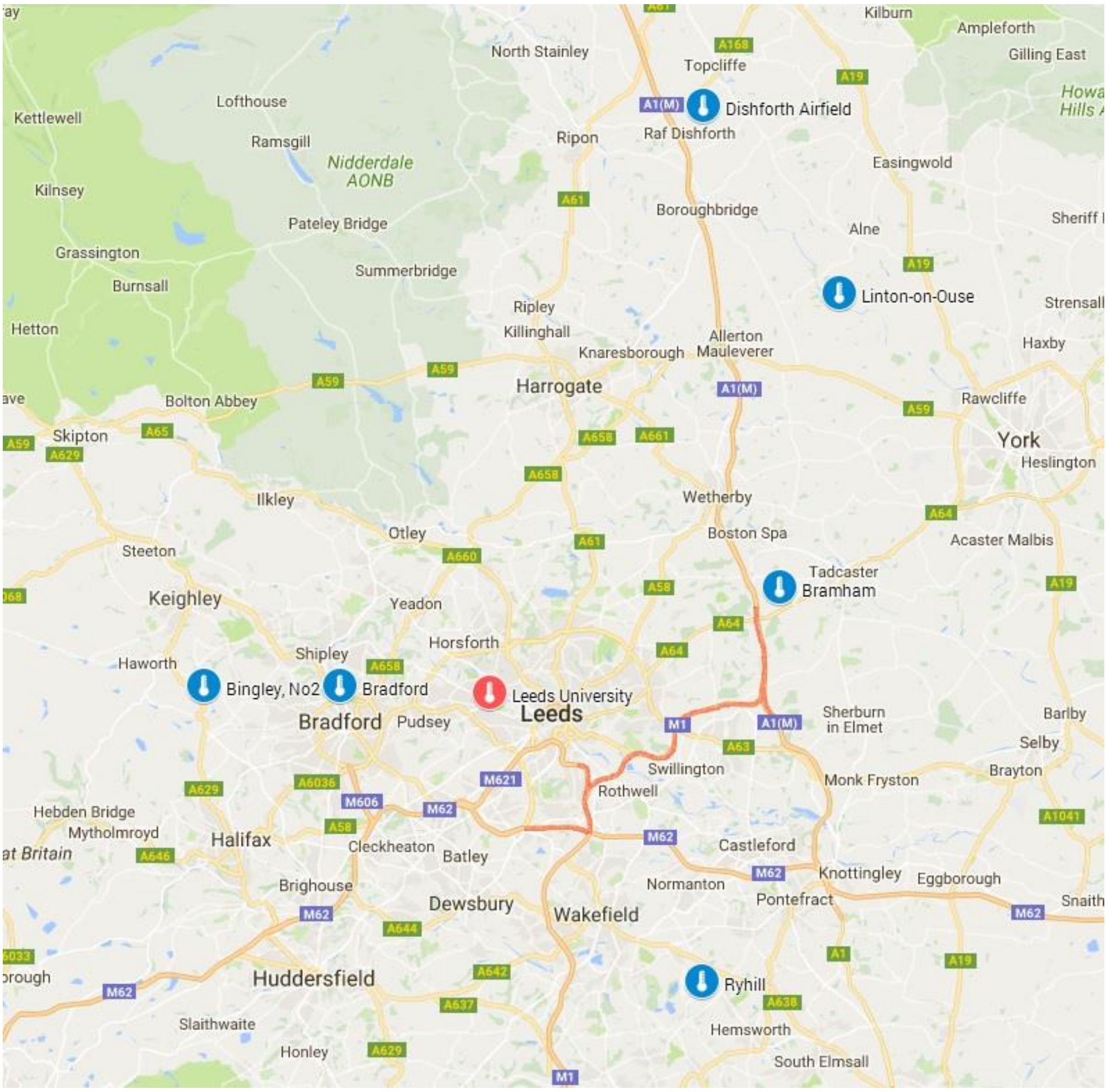

Figure E1 Locations of the weather stations in the proximity of the M1-A1 Link Road

Table E1 Values of 'precipitation/rain state' variable.

Precipitation/ Rain state	Physical meaning
None	No precipitation
Recent precipitation	Precipitation occurred between the previous observation and this latest report
Current precipitation	Precipitation reported at the time of the observation
Light precipitation	Intensity less than 2mm per hour
Medium precipitation	Intensity in the range 2 – 4mm per hour
Heavy precipitation	Intensity greater than 4mm per hour
Light snow	Intensity as above but for frozen precipitation and for water equivalent
Medium snow	Moderate intensity, frozen precipitation
Heavy snow	Heavy snowfall, rapid accumulation

Table E2 Values of 'surface state' condition variable.

Surface state condition	Physical meaning
Dry	Surface is dry
Moist	Surface is moist. Typically, asphalt roads will appear darker than normal
Wet	Surface is wet. Asphalt roads may glisten with reflected light. There may be standing liquid water present on the road
Wet and Treated	Liquid water containing de-icing chemical is present on the road surface
Frost	Hoar frost detected. A heavy deposit of frost will leave the road with a coating of white ice crystals, effectively giving asphalt a gray appearance when viewed in daylight
Snow	Snow detected on the road surface
Ice	Mono-crystalline ("black") ice detected. Formed by the freezing of water insitu, this generally comprises a layer of clear ice, so an asphalt road surface will appear black
Trace or moist and treated	Road surface moist and there is de-icing chemical present. Typically, this is seen when a road is in transition between a "dry" and "moist" or "wet" state

Table E3 Values of ‘alarm state’ variable

Alarm state condition	Physical meaning
None	No warnings or alarms
Precipitation Warning	Precipitation (rain, snow etc.) detected recently and there may be subsequent freezing, as the surface temperature is close to or below freezing
Frost Warning	Surface temperature is below freezing and below the dew point temperature. Hence hoar frost is either present or can be expected to form shortly
Ice Warning	Surface is close to freezing or ice and or frost formation will occur within a given period if the current trend continues
Ice Alarm	Surface at or below freezing point; either there is ice/frost already or there will be very soon

APPENDIX F: PAPER 1

Exploring the factors affecting motorway accident severity in England using the generalised ordered logistic regression model

Full Reference

Michalaki, P., Quddus, M, Pitfield, D. & Huetson, A, 2015. Exploring the factors affecting motorway accident severity in England using the generalised ordered logistic regression model. *Journal of Safety Research*, 55, 89-97. http://doi.org/10.1016/j.jsr.2015.09.004

Abstract

Problem

The severity of motorway accidents that occurred on the hard shoulder (HS) is higher than for the main carriageway (MC). This paper compares and contrasts the most important factors affecting the severity of HS and MC accidents on motorways in England.

Method

Using police reported accident data, the accidents that occurred on motorways in England are grouped into two categories (i.e., HS and MC) according to the location. A generalized ordered logistic regression model is then applied to identify the factors affecting the severity of HS and MC accidents on motorways. The factors examined include accident and vehicle characteristics, traffic and environment conditions, as well as other behavioral factors.

Results

Results suggest that the factors positively affecting the severity include: number of vehicles involved in the accident, peak-hour traffic time, and low visibility. Differences between HS and MC accidents are identified, with the most important being the involvement of heavy goods vehicles (HGVs) and driver fatigue, which are found to be more crucial in increasing the severity of HS accidents.

Practical applications

Measures to increase awareness of HGV drivers regarding the risk of fatigue when driving on motorways, and especially the nearside lane, should be taken by the stakeholders.

Keywords: Accident severity; Motorway; Hard-shoulder; Generalized ordered logit model; Fatigue

Paper type: Published peer-reviewed journal

1. INTRODUCTION

The hard-shoulder of a motorway - also called shoulder or emergency lane - can be used either by the public for emergency reasons or by the public agencies and private companies that are responsible for the maintenance and operation of the road. In many past campaigns aimed at both the public and the operatives, it has been highlighted that the hard-shoulder is a hazardous place either to stop or drive *(SURVIVE Group, 2006)*; however, this has not been investigated through rigorous research. Significant research has been conducted in the area of road safety generally, and especially motorway safety. Many studies have focused on the severity of motorway accidents since historical data suggest it is higher than those that occur on the rest of the road network *(SURVIVE Group, 2006).*

In Great Britain, the severity of accidents has three categories: slight, serious and fatal injury. Motorway accidents can be divided into two groups according to the location where the initial impact happened: *hard-shoulder (HS)* and *main carriageway (MC)*. When comparing the level of accident severity of these two groups in Great Britain, it can be concluded that the severity of HS accidents is significantly higher. More specifically, the percentage of accidents on the HS that are fatal is almost five times than for the MC and the proportion of serious injury accidents is also relatively high on HS. However, no significant research has been conducted in the past on the factors affecting the severity of hard-shoulder accidents.

The aim of this study is to investigate the main factors affecting the severity of accidents in these two distinct zones of the motorways and to identify any differences between them. In this context, focus is drawn on a number of factors that are commonly reported as important in road accidents. These are driver fatigue, accidents involving Heavy Goods Vehicles (HGVs) and driver errors.

The rest of the paper is organised as follows: the next section provides a discussion on the factors that are commonly reported as important in road accidents, followed by the statistical methods used in this study. Then the estimation results along with a discussion on the findings are presented. The paper ends with a conclusion and relevant practical applications of the work.

2. FACTORS AFFECTING ROAD ACCIDENTS

Identifying causes of accidents and possible factors that increase the accident risk for the driver improves the development of countermeasures related to traffic safety *(Häkkänen & Summala, 2000).* The factors affecting road accident severity are generally divided into two categories: *engineering* (road/ vehicle/ environment related) and *human*.

Engineering factors refer to *road infrastructure characteristics*, *traffic conditions* and *ambient conditions*. The relationship between road traffic accidents and geometric design variables, such as curvature, vertical grade, lane width, and hard-shoulder width has been empirically investigated through statistical models in several studies *(Haynes, Jones, Kennedy, Harvey & Jewell, 2007; Kononov, Bailey & Allery, 2008).* Regarding traffic statistics, speed appears to be important for both the severity and frequency of accidents and is included in several alternative forms, for instance average speed, speed limit and speed variation *(Elvik, Christensen & Amundsen, 2004; Aarts & van Schagen, 2006)*. Traffic is also expressed using a range of variables, such as traffic flow, traffic density and congestion

(Golob & Recker, 2003; Wang, Quddus & Ison, 2009). Inclement prevailing weather conditions appear to be quite significant for road accidents in various aspects, namely precipitation, wind and fog. Road vehicles in strong winds can experience a variety of problems depending upon the vehicle type, shape and the wind dynamic *(Edwards, 1994)*, while rainfall is suggested to affect drivers in different ways across different geographic areas and times of the day *(Brijs, Karlis and Wets, 2008)*.

Human factors also play a very important role in road accidents. In general, different groups of drivers have a different risk of being involved in an accident. HGV drivers have been proved to be in the high risk group *(Charbotel, Chiron, Martin & Bergeret, 2002)*. In the United Kingdom (UK), fatal road accidents per 100 million vehicle kilometres involving HGVs are almost double of those involving cars *(Department of Environment, Transport and the Regions, 1998)*. Identifying risky drivers could facilitate more effective traffic safety work and allow measures to be tailored towards a specific driver group.

Driver Fatigue appears to be one of the most often reported factors in road accidents. According to Karrer and Roetting *(2007)* falling asleep at the wheel is one of the leading causes of fatal accidents and injuries, accounting for up to 15–20% of all traffic accidents in developed countries. However, it is often overlooked in police reports, as some drivers are deceased in the accidents, while surviving ones may be unwilling to admit that they were asleep behind the wheel *(Corfitsen 1999)*. HGV drivers are a sensitive group fatigue wise. Several previous studies have reported that they face fatigue-related problems while driving *(Häkkänen & Summala, 2000; Zhang & Chan, 2014)* and the drivers themselves recognise it *(Häkkänen & Summala, 2001)*.

Nordbakke and Sagberg's study *(2007)* showed that most drivers experience various symptoms of sleepiness, such as difficulty keeping their eyes open, before they fall asleep while driving. However, those symptoms are not taken seriously enough; this may be due to an underestimation of the relation between the various physiological and behavioural signals. Even though drivers often fight the symptoms of sleepiness even before the trip, they sometimes overestimate their own capability. In spite of the drivers' knowledge of the risk, most drivers continue to drive even when recognising sleepiness while driving. The justification for this is most commonly related to the distance to be driven – total or remaining *(Nordbakke & Sagberg, 2007)*. Horne and Reyner have contributed to the establishment of permanent awareness signs on the British motorways stating that 'Tiredness Can Kill' and encouraging drivers to take a break *(Horne & Reyner, 2001)*.

Several studies have also been conducted in order to correlate the accidents (both frequency and severity) with their causes or contributory factors. However, there is no previous significant research referring to accidents that happen specifically on the HS. These incidents have not been thoroughly examined to determine their specific primary causes or their contributory factors and how these have an effect on level of severity.

3. STATISTICAL MODELS

Accident severity is, usually, defined as a categorical variable; the values of which vary according to the method which is officially suggested by the authorities designing and collecting accident data. These values represent the 'level of severity' in an ordinal scale (e.g. no injury, slight injury, serious injury, fatality). In GB, accident severity is recorded as *slight*, *serious* and *fatal*. For this study, discrete choice modelling, in which a decision maker chooses an alternative from a set of exhaustive and mutually exclusive alternatives *(Train, 2009)*, can be chosen in order to explore the most important factors affecting the severity of accidents on British motorways. In the case of road accident severity models, researchers are trying to explore the factors which can be related to road characteristics, the users, the vehicles or the conditions on the road at the time of the accident.

When the dependent variable (accident severity) is discrete and contains more than two categories, the multinomial logistic regression (logit) model is a well-established method to use *(e.g. Khorashadi, Niemeier, Shankar & Mannering, 2005)*. The multinomial logit model combines the independent variables to estimate the probability that a particular event will occur; in this case the probability of an accident to be slight, serious or fatal. When the order of the values is taken into consideration, thus hierarchy has a natural meaning, such as in this study, the commonly used model is an ordered logistic regression *(Quddus, Wang & Ison, 2010)*.

If the data are nested, such as accidents nested within roads and roads nested within areas (e.g. a census tract), the use of *multilevel ordered logit models* would be more appropriate. Such models can allow a possible correlation structure among a set of observations from the same level *(Dupont, Papadimitriou, Martensen & Yannis, 2013;Lord & Mannering, 2010)*. Based on the data hierarchy, the first decision concerns the choice of the levels of analysis. Formulated generally, a level is a set of units, or equivalently a system of categories, or a classification factor in a statistical design. In order to justify the use of the multilevel model, the significance of the Intra-class Correlation Coefficient (ICC) must be tested. In the case of a two-level model, one ICC can be estimated. It varies from 0 to 1 and indicates whether the multiple levels are appropriate for the data, as it shows the similarity of observations within a group.

Intercorrelation among accidents that share some common characteristics has not been widely examined in past studies *(Savolainen, Mannering, Lord & Quddus, 2011)*. In this study, the inter-correlation among the accidents that occur in the same geographical area is captured. The area variable chosen to group correlated motorway accidents is county (Figure 1). Counties derive from the geographical and administrative area division system in GB. Since this system does not appear to be cohesive throughout, only data from England are used.

The *multilevel mixed-effects ordered logit* model allows for many levels of nested clusters of random effects. A quantity being random means that it fluctuates over units in some population, and which particular unit is being observed depends on chance. In this case, the coefficients of the model are not standard (fixed) for the whole sample, but they follow a distribution and conclusions are drawn about the population from which the observed units were drawn, rather than about these particular units themselves. It allows the model to account for unobserved effects that are difficult to quantify and may affect the model estimation *(Ye & Lord, 2014)*.

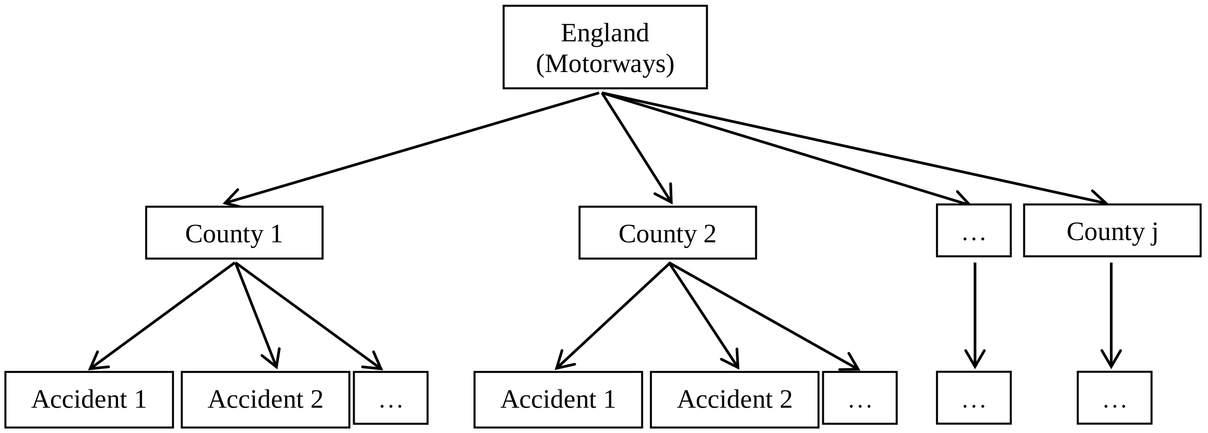

FIGURE 1 Multilevel model for motorway accidents in England.

In the two-level model, random effects of the accidents clustered in the English counties can be specified. The model estimates the possibility of an accident having a specific level of severity, given that the accident has occurred in a certain county - the second level of the model. For a series of independent clusters, and conditional on a set of fixed effects x_{ij}, a set of cut-points κ that define the limit values between the different categories, and a set of random effects u_j, the probability of the response y_{ij} being in a category m is:

$$p_{ij} = \Pr(\mathrm{y_{ij}} = m|\kappa, u_j) = \Pr(\mathrm{\kappa_{m-1}} < x_{\mathrm{ij}}\beta + z_{ij}u_j + \varepsilon_{ij} \leq \kappa_m)$$
$$= \frac{1}{1+\exp(-\mathrm{\kappa_m}+n_{\mathrm{ij}})} - \frac{1}{1+\exp(-\mathrm{\kappa_{m-1}}+n_{\mathrm{ij}})} \qquad (1)$$

where j = 1, ..., J clusters (i.e. counties), with cluster j consisting of i = 1, ..., $\mathrm{n_j}$ observations (i.e. accidents).

The model in terms of a latent linear response, where observed ordinal responses y_{ij} are generated from the latent continuous responses, is written as:

$$y_{ij}^* = x_{ij}\beta + z_{ij}u_j + \varepsilon_{ij} \qquad (2)$$

$$y_{ij} = \left\{ \begin{array}{lllll} 1 & if & -\infty & \leq y_{ij}^* < & \kappa_1 \\ 2 & if & \kappa_1 & \leq y_{ij}^* < & \kappa_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ m & if & \kappa_{m-1} & \leq y_{ij}^* < & \kappa_m = \infty \end{array} \right\} \qquad (3)$$

The errors $\varepsilon_{\mathrm{ij}}$ are distributed as logistic with mean 0 and variance $\pi^2/3$ and are independent of $\mathrm{u_j}$. The model is estimated using the adaptive Gauss-Hermite quadrature estimation.

When there are no theoretical or other prior guidelines about which variables should have a random effect, the researcher can be led by the substantive focus of the investigation, the empirical findings and the parsimonious modelling. This implies that those explanatory variables that are especially important -or have especially strong effects- could be modelled with random effects if the variances of these effects are important enough, as evidenced by their significance and size. Nonetheless one should take care that the number of variables with random effects should not be so large that the model becomes unwieldy *(Snijders & Bosker, 1999; Snijders, 2005).*

In cases where there is no identified inter-relationship among the observations, according to ICC, and/or a higher level random intercepts are statistically insignificant, a *single level ordered logit* should be used. However an important underlying assumption of the ordered logit model is the parallel regression assumption. Accordingly the relationship between each pair of outcome groups (e.g. slight vs. serious and fatal; slight and serious vs. fatal) is the same. This assumption can be tested using the Brant test, which provides evidence if it is violated *(Brant, 1990)*. In this case, the results of a simple ordered logit model can lead to incorrect or misleading results and a different model should be applied that allows the relaxation of the parallel regression assumption.

Such an alternative is the *generalised ordered logit* model. This model’s advantage is that it does not impose the parallel regression assumption, which is an important limitation of the ordered logit model. In this model, the coefficients of the variable vary among the categories of the variables. If this is not the case for all the variables, the model is called partially constrained. It has been recommended by Eluru *(2013)* for the case of ordinal data and has been adopted in the area of road safety *(Wang, Quddus & Ison, 2009; Abegaz, Berhane, Worku, Assrat & Assefa, 2014).*

In the partially constrained generalised ordered logit model, only a subset of variables has a varying coefficient, the ones that violate the aforementioned assumption. The generalised ordered logit model can be written as follows (Williams, 2006):

$$P(Y_i > j) = \frac{\exp(a_j + X_i\beta_j)}{1+\exp(a_j + X_i\beta_j)}, j = 1,2,\dots,m-1 \tag{4}$$

where m is the number of categories of the ordinal dependent variable, while the partially constrained model as:

$$P(Y_i > j) = \frac{\exp(a_j + X_{1i}\beta_j + X_{2i}\beta_2)}{1+\exp(a_j + X_{1i}\beta_j X_{2i}\beta_2)}, j = 1,2,\dots,m-1 \tag{5}$$

In the last model, the first subset of variables has a non-constrained coefficient across the values, and the second subset has the same coefficient across the values of *j*. For the case of a dependent variable that has 3 values (e.g. 1, 2, 3), two panels of coefficients are provided as if the variable is recoded as 1 vs. 2+3 and 1+2 vs. 3. Positive coefficients suggest that higher values on the independent variables make higher values on the dependent variable more likely. The parameters are estimated using the maximum likelihood estimation technique.

4. ACCIDENT DATA DESCRIPTION

In GB, all road accidents involving fatalities or personal injury, in which one or more vehicles are involved, are notified within 30 days of occurrence to the Police, who attend the scene and collect the data required. Details recorded are organised in three datasets which include complete information on the *accident* itself, the *casualties* (any persons injured or killed) and every *vehicle* involved or contributing to the accident. The subsequent collated output reports, entitled STATS19, have been available since 1985.

For this study, the three sub-sets are merged, using the accident and vehicle reference numbers provided. The unit of analysis is the *accident*. After merging though, if there are more than one record per accident (in cases that there are more than one vehicle involved or more than one casualty), thus the duplicates are removed. Motorway accidents are then extracted from the whole database and divided into two groups: (1) accidents that occurred on the MC and (2) accidents that occurred on the HS (i.e. entering, leaving or parked on the HS). From 1985 to 2011, there were a total of 199,388 accidents (in which 2.3% were fatal, 13.0% serious injury and 84.7% slight injury accidents) on GB motorways.

The distinction between the HS and MC accidents is based on the location where the accident happened. As described in STATS20 – the document for the specification of the variables included in STATS19 – an accident should be located where the *first* impact occurred. For instance, an accident where two vehicles on the MC collide and one ends up on the HS is not located as a HS accident.

The dependent variable of the models is '*severity of accident*', a discrete variable that can obtain three values: *slight injury*, *serious injury* and *fatality*. Fatal injury includes the cases where death occurs in less than 30 days as a result of the accident. Serious injuries are those where either immediate or later detention in hospital as an in-patient, was required.

For this study, new variables were created to keep more detailed information regarding the vehicles involved in the accident. These variables refer to whether the accident involved one vehicle or more, at least one HGV, at least one left-hand-side drive vehicle or whether roadworks were present at the time of the accident. For instance, if at least one HGV was involved in an accident, the variable has the value 1 and 0 for the opposite. Also, in order for the models to be estimated, all categorical variables were transformed into the required number of dummy variables (day of the week, month, speed limit, traffic, weather, surface and light conditions). Trend is also included in the model as a yearly dummy variable.

Since 2005, the Police were asked to record additional data, more subjective and related to drivers, vehicle or road characteristics; these are known as the Contributory Factors. These are factors in a road accident – in the opinion of the attendant police officer – that are the key actions and failures that led directly to the actual impact. They postulate why the accident occurred and give clues about how it may have been prevented. In comparison to the Accident, Vehicle and Casualty record sets, which mainly record objective details, the *Contributory Factors* depend on the skill and experience of the investigating officer to reconstruct the events which led directly to the accident. While instructions are also provided, factors should be identified on the basis of evidence rather than guess-work about what may have happened. Up to 6 factors are collected for each accident. They are clustered in certain categories according to STATS20; however, a different grouping was followed in this study, in order to minimise the number of categories and to create more cohesive groups. In addition, as special focus is given to fatigue, a single category only for this is created.

The groups of contributory factors which are studied are related to:

- *driver/rider fatigue*, which in the initial police records comes under the impairment category, but is individually examined in this study;
- *driver/rider error* (e.g. failed to look properly, failed to judge other person's path or speed, sudden braking, swerved, loss of control, nervous or uncertain behaviour, learner or inexperienced driver);

- *driver/rider behaviour (aggressive or illegal)* (e.g. exceeding speed limit, travelling too fast for conditions, aggressive, careless, reckless driving or in a hurry);
- *driver/rider impairment* (e.g. impaired by alcohol/drugs, defective eyesight, illness);
- *road conditions* (e.g. poor road surface, foreign deposit on the road, slippery road due to weather, road layout, vision affected by dazzling headlights/sun/rain);
- *vehicle* (e.g. tyres illegal or defective, defective lights/indicators/brakes,/steering/ mirrors, overloaded or poorly loaded vehicle or trailer);
- *distraction* (e.g. driver using mobile phone, eating/drinking, distraction outside the vehicle); and
- *pedestrians.*

Multicollinearity among the contributory factors was checked via the calculation of pair-wise correlations. Only error and behaviour factors were found to have high correlation in both datasets (0.87 for HS and 0.88 for MC accidents). Thus, these two variables were not included in the models simultaneously.

The data used for both models are from 2005 to 2011. Table 1 provides the frequencies and severity of the accidents for the period examined. It is noted that the severity of HS accidents is significantly higher than the MC, as the relative frequency of HS accidents is almost 5 times higher. The absolute frequency of HS accidents might be quite low; however, when these accidents occur, it is quite probable they tend to a serious or fatal injury. The relative frequencies of some characteristics between HS and MC accidents are significantly different. For instance, out of all the *fatal accidents*, the percentage of those that involved driver's fatigue is double on the HS than the corresponding percentage for MC accidents (23.08% vs. 11.63%). Other such examples are for **fatal** accidents:

- *HGVs*: **80%** HS while **44.36%** MC
- *Single-vehicle accidents*: **7.69%** HS while **39.09%** MC
- *Morning peak traffic:* ***13*.55%** HS while **7.69%** MC
- *Pedestrian(s) involved*: **15.38%** HS while **9.83%** MC
- *Contributory factor 'Road'*: **18.46%** HS while **8.39%** MC

For other variables such as the surface condition the above ratios are similar for HS and MC accidents; i.e. 70% of the fatal accidents occur when the surface is dry and the remaining 30% when the opposite is true (e.g. wet, flooded etc). If all, and not only fatal, accidents are taken into consideration, the ratios are sometimes substantially different; e.g. the percentage of **all** accidents that are single-vehicle is 22.49% for MC and 19.07% for HS.

TABLE 1 Frequency and Relative Frequency of Main Carriageway and Hard-Shoulder Accidents in terms of Severity (2005-2011).

Severity	Frequency of MC accidents	% Relative Fr.	Cumulative Fr.
Slight (=1)	41,576	88.28	88.28
Serious (=2)	4,684	9.95	98.23
Fatal (=3)	834	1.77	100.00
Total MC accidents	47,094	100.00	

Severity	Frequency of HS accidents	% Relative Fr.	Cumulative Fr.
Slight (=1)	556	71.65	71.65
Serious (=2)	155	19.97	91.62
Fatal (=3)	65	8.38	100.00
Total HS accidents	776	100.00	

5. ESTIMATION RESULTS AND DISCUSSION

The statistical models are applied to the HS and MC motorway accidents separately and the relationships between the levels of severity of these accidents are explored with a series of explanatory variables. As mentioned earlier, the unit of analysis is the *accident*. The models that are initially tested are the simple ordered logit model and the multilevel ordered logit model. Firstly, all the independent variables considered to be potentially significant and have an effect on accident severity are included in the model. A random intercept multilevel ordered logit model was initially estimated and then, as a second step, the random effects of the independent variables are included in the model one at a time. After all the variables have been tested independently, models that include two or more independent variables with possible random effects are estimated. However, the ICC was found to be low (i.e. 0.016 for MC accidents and 0.1 for HS accidents) suggesting that the correlation among the accidents that occur in the same county is not strong enough to support the use of the multilevel model. Therefore, a single-level model is then considered.

The ordered logit model, when the Brant test is used, is also considered inappropriate for this study, as the parallel regression assumption is violated. Thus, it is necessary to apply the generalised ordered logit model, and more specifically, the partially constrained model. In these models, as there are three categories in the dependent variable (M=3), two coefficients (M-1) are estimated for each of the explanatory variables that violated the parallel regression assumption: one coefficient represents the effect of an explanatory variable on the outcome of slight injury relative to serious and fatal and the other coefficient indicates the effect of the same explanatory variable on the outcome of slight and serious relative to fatal. The models for the MC and HS accidents are separately estimated while following the same process as above with the explanatory variables. Only the statistically significant variables are kept in the final models.

Table 2 presents separately the results for the two partially constrained generalised ordered logit models for the two groups of accidents. The variables kept in the model are those whose parameters are statistically significant at the 90% level. An alternative parameterisation, called Gamma (γ), provides a more parsimonious layout and another way of understanding the parallel regression assumption is employed *(Peterson & Harrell, 1990)*. In this alternative parameterisation, *Beta* coefficients refer to the effect of variables that have the same coefficients for all possible pairs of outcome categories, while *Gamma* coefficients refer to the differential effect of the variables on each pair of outcomes. The Gammas indicate the extent to which the parallel regression assumption is violated by the variable. Thus, if

Gammas are statistically different from 0 for an explanatory variable, then the parallel regression assumption is considered to be violated for this variable. If all Gammas are equal to 0, the model would reduce to the ordered logit model. Table 3 presents the marginal effects which show the probabilities of having a specific outcome with respect to changes in the dependent variables. The variables included in the table are the ones with non-zero Gammas plus fatigue and two variables with high marginal effects in comparison to the others: number of casualties and single-vehicle accidents.

Accident Characteristics

The explanatory variables are grouped in categories. Regarding the accident characteristics in the MC model, the variables referring to the *number of vehicles*, *number of casualties* as well as *single-vehicle accidents* are significant. In the case of HS accidents, only the *number of casualties* appears to be significant, while having a higher coefficient than MC. These three variables all have a positive coefficient, affecting in an increasing way, the severity of accidents if all else are held constant. In terms of the *number of vehicles* involved in an accident for the case of MC model, the variable does not have the same effect across both pairs of outcome categories, which would not have been found if the simple ordered logit model was employed. The Beta coefficient for *number of vehicles* is 0.0549 denoting the effect of this variable on the slight vs. serious and fatal outcome. The Gamma value for the variable is 0.0545 suggesting that the effect of this variable on the slight and serious injury vs. fatal outcome is 0.1094 (i.e. 0.0549 + 0.0545). The severity of accidents is decided according to the most severe casualty. Thus, accidents that have only slight injuries, regardless of the *number of casualties*, are recorded as slight injury accidents. The results of the MC model suggest that the higher the *number of casualties*, the higher the possibility of the accident to be serious or fatal, which is also shown from the marginal effects being positive for these two outcomes.

Vehicle Characteristics

The next set of variables refers to the characteristics of the vehicles embroiled in the accident; both variables refer to whether at least one of the following types of vehicles was involved: *HGVs* or *left-hand-side drive vehicles*. *HGVs* appear to have a positive coefficient, suggesting that the severity of accident is increased when there is at least one HGV vehicle involved. HGVs do have the ability to ‘protect’ its own occupants due to the size and structure of the vehicle; however, for the same reasons it causes a more serious impact to the other vehicles involved *(Öz, Özkan & Lajunen, 2010).* It is worthwhile to note that in the case of HS accidents, this variable has a much greater effect and also has a varying coefficient for the second threshold. In opposition to HGVs, *left-hand-side driving vehicles* tend to reduce the level of severity of accidents. The opposite result could be expected due to added difficulty of driving or inexperience of foreign drivers in the British driving system. However, a possible explanation for this result can be that these drivers are more cautious while driving in a non-familiar environment and from their driving position have a better visibility of the HS.

Seasonality

Another set of variables that appears to have a significant effect on the severity of MC accidents is the *day of the week* when the accident happened. From the results of the models, it is shown that during working days, the accidents are less severe than during the weekend. Different relationships have been suggested for this. For instance, Quddus *(8)* concluded that accidents on the M25 motorway, around London, are more severe on weekdays, while Gray et al. *(Gray, Quddus & Evans, 2008)* had estimated the opposite, which is consistent with this study.

TABLE 2 *Gologit2* Model Results for Main Carriageway and Hard-Shoulder Accident Severity.

			Main Carriageway		***Hard-Shoulder***	
		Explanatory Variables	**Coef.**	**z**	**Coef.**	**z**
Beta	*Accident Characteristics*	Number of vehicles	0.0549	3.55	*na*	*na*
		Number of casualties	0.2802	23.83	0.3570	6.33
		Single vehicle accident	0.9494	22.53	*na*	*na*
	Vehicle Characteristics	**Heavy Goods Vehicle**	0.3353	9.54	0.7565	4.08
		Left-hand-side drive	-0.2858	-3.82	*na*	*na*
	Seasonality	Saturday	0.1275	2.93	0.5301	2.19
		Sunday	0.1649	3.88	*na*	*na*
		Reference: Friday				
		April	0.0969	1.76	*na*	*na*
		July	*na*	*na*	0.4712	1.71
		August	0.1811	3.61	*na*	*na*
		September	*na*	*na*	0.6980	2.18
		Reference: December				
	Traffic Characteristics	Traffic peak morning	-0.2837	-4.76	*na*	*na*
		Traffic peak afternoon	-0.4111	-7.34	*na*	*na*
		Traffic peak normal	-0.3627	-7.23	*na*	*na*
		Reference: Traffic non peak				
		Speed limit 70mph	0.6365	3.85	*na*	*na*
		Speed limit 60mph	0.6962	3.51	*na*	*na*
		Speed limit 50mph	0.5601	3.12	*na*	*na*
		Reference: Speed limit 40mph or lower				
	Conditions on the motorway	Daylight	-0.2825	-5.89	-0.4982	-2.86
		Dark and lights on	-0.2909	-5.80	*na*	*na*
		Reference: Dark and no lights				
		Surface dry	0.1324	3.15	*na*	*na*
		Reference: Surface non-dry				
		Weather fine	0.1509	3.01	*na*	*na*
		Weather fog	0.3199	2.10	*na*	*na*
		Reference: Weather other				
		Roadworks	-0.2917	-3.56	-1.2136	-2.75
	Contributory Factors	**CF fatigue**	0.3891	6.91	0.7928	3.43
		CF error	0.0736	2.36	*na*	*na*
		CF impairment	0.6468	11.58	*na*	*na*
		CF distraction	0.1756	2.49	0.6727	2.26
		CF pedestrian	1.4370	13.09	2.0541	5.14
		CF vehicle	0.1372	1.91	*na*	*na*
		CF other	0.2538	3.81	*na*	*na*
		Reference: CF road				
Gamma_2		Number of vehicles	0.0545	3.07	*na*	*na*
		Heavy Goods Vehicle	0.4001	5.80	0.6750	2.10
		Saturday	0.1986	2.30	*na*	*na*

	Traffic peak afternoon	-0.2098	-2.06	*na*	*na*
	Daylight	-0.3800	-5.57	*na*	*na*
	CF error	-0.1901	-2.83	*na*	*na*
	CF pedestrian	1.0940	9.80	*na*	*na*
	CF distraction	0.2790	2.09	*na*	*na*
Alpha	Constant 1	-3.5187	-19.80	-2.0502	-9.37
	Constant 2	-5.6330	-29.22	-4.2689	-11.87
Summary statistics	Log likelihood	-17984.448		-522.214	
	Pseudo R squared	0.0708		0.1241	
	Number of observations	*47094*		*776*	

na=non-applicable

Traffic Characteristics

Since no detailed traffic data were available, the way of incorporating this information in the model was by creating four variables according to the hour that the accident happened. These were based on historical data of *peak in the morning*, the *late afternoon peak*, *normal* and *non-peak* (quiet) traffic hours. The model illustrates that if the hour is non-peak, the severity tends to be higher. This might be related to speed which is generally higher during non-peak hours and is frequently related to more severe and fatal accidents *(Elvik, Christensen & Amundsen, 2004).* The reference variable for this set was non-peak and the rest of the variables appeared to have a negative coefficient. In addition, 'traffic peak afternoon' has a different second coefficient; the Gamma value is negative suggesting that the probability of having a fatal accident is even lower. However, the difference between serious/fatal is lower than slight/serious, as it is suggested by the marginal effects.

Another traffic related variable is *speed limit*. When comparing the higher speed limits with the variable left out of the model, which represents a speed limit of 40mph or lower, it is suggested that higher speed limits cause an increase of the level of severity of the road accidents. Past studies have shown contradictory results regarding the relationship between speed and accident severity, thus more research is required in this field *(Wang, Quddus & Ison, 2013).*

Conditions on the Motorway

Regarding *lighting conditions*, the same conclusions as previous studies are drawn; it is supported that the presence of lights (daylight or street lighting) has an effect on the accident severity by decreasing it; thus it is expected to have lower severity of accidents when visibility on the motorway is better.

Two types of *road surface conditions* were considered: dry and non-dry. The latter includes snow, frost and flood. It is estimated that when the condition of the surface is dry, it is more possible to have a more severe accident, which is consistent with other studies *(Quddus, Wang & Ison, 2010).* This result is plausible, as under adverse surface conditions, drivers tend to drive at a lower speed and awareness in generally increased. Similarly, when weather is fine, accidents tend to be more severe for the case of MC accidents, as the variable is significant with a positive coefficient. Wind was also tested in the initial models, but did not appear to be significant in any.

TABLE 3 Marginal Effects.

Marginal Effects	Explanatory variable	***Main Carriageway***		***Hard-Shoulder***	
		Coef.	z	Coef.	z
Slight injury	Number of vehicles	-0.0050	-3.55	*na*	*na*
	Number of casualties	-0.0256	-23.88	-0.0692	-6.18
	Single-vehicle accident	-0.1075	-19.00	*na*	*na*
	Heavy Goods Vehicle	-0.0321	-9.17	-0.1447	-4.21
	Saturday	-0.0121	-2.82	-0.1115	-2.05
	Traffic peak afternoon	0.0344	8.02	*na*	*na*
	Daylight	0.0271	5.63	0.0995	2.79
	CF fatigue	-0.0409	-6.07	-0.1726	-3.16
	CF error	-0.0067	-2.37	*na*	*na*
	CF pedestrian	-0.2196	-9.26	-0.4722	-5.91
	CF distraction	-0.0171	-2.34	-0.1464	-2.08
Serious injury	Number of vehicles	0.0037	2.94	*na*	*na*
	Number of casualties	0.0223	23.51	0.0515	5.71
	Single-vehicle accident	0.0926	19.08	*na*	*na*
	Heavy Goods Vehicle	0.0222	6.90	0.0718	2.31
	Saturday	0.0078	1.96	0.0799	2.11
	Traffic peak afternoon	-0.0282	-7.16	*na*	*na*
	Daylight	-0.0181	-4.27	-0.0729	-2.79
	CF fatigue	0.0355	6.10	0.1204	3.34
	CF error	0.0081	3.07	*na*	*na*
	CF pedestrian	0.1025	5.45	0.2339	8.77
	CF distraction	0.0105	1.57	0.1026	2.21
Fatal injury	Number of vehicles	0.0013	4.85	*na*	*na*
	Number of casualties	0.0033	18.06	0.0178	4.99
	Single-vehicle accident	0.0149	14.75	*na*	*na*
	Heavy Goods Vehicle	0.0099	8.48	0.0729	4.44
	Saturday	0.0043	3.11	0.0316	1.82
	Traffic peak afternoon	-0.0063	-6.32	*na*	*na*
	Daylight	-0.0090	-7.19	-0.0265	-2.54
	CF fatigue	0.0054	5.72	0.0522	2.56
	CF error	-0.0014	-1.60	*na*	*na*
	CF pedestrian	0.1171	7.74	0.2383	2.97
	CF distraction	0.0066	2.60	0.0438	1.75

na=non-applicable

'Roadworks' is a variable that represents whether they were present at the time of the accident. This variable is significant in both models, while having a much greater effect in the HS model. It is estimated that if roadworks are present, the severity of an accident tends to drop. Again, this can be attributed to the speed restrictions that are always imposed in these instances, as well as the drivers being more cautious. It has to be noted that if an accident happens in a closed lane that is normally running, the accident is still considered a HS accident.

Contributory Factors

Even though these data are partially subjective and based on the police officer's judgement, they can still provide useful information. Since the contributory factors are represented by a group of dummy variables, as described earlier, one of the dummy variables must be left out of the model. The variable representing the factors related to the *road* is chosen not to be included, as it is the factor that is least related to the driver. All contributory factors' variables have a statistically significant coefficient and present the same sign. As it can be noticed, the highest coefficient is the one related to *pedestrians* involved in the accident. As this group of people is the most vulnerable, it is expected when a pedestrian is involved, for the accident to be more severe. After pedestrians the next highest coefficients belong to *impairment* and *fatigue* which play an important role in road accidents by increasing significantly their severity *(Evans, 1991).*

Driver fatigue is a significant factor for both the MC and HS models. Whilst it is the second most important contributory factor in HS accidents, after 'pedestrians', in the HS model, it is a much more important factor, as the value of the coefficient is substantially higher at 0.79, while it is 0.39 for MC accidents. Past studies *(e.g. Häkkänen H., and Summala, H.)* have shown that very often HGV drivers feel tired while driving. This can be the result of long and monotonous journeys or the inability to stop due to timetable restrictions. It is crucial for HGV drivers to be aware of fatigue being such an important attribute of HS accidents. The marginal effects are negative for slight injury, both for MC and HS accidents, whilst they are positive for serious and fatal injuries. They are also much higher for the case of HS. For instance, the marginal effects of fatigue for fatal injury are 0.0054 and 0.0522 for MC and HS respectively; thus, if the value of dummy variable 'fatigue' changes from 0 to 1, the possibility of having an accident to be fatal is getting 0.54% higher for the MC and 5.2% higher for the HS.

Error and *behaviour* related factors appear to have a very high correlation (0.88 for MC and 0.87 for HS), thus it was important to control whether one for these variables should be removed from the model. After including each of them individually and both together, it was concluded that only one should be kept; error is the selected one, as it is of a high interest and also has a varying coefficient. The high correlation between the factors above shows that most of the time they occur in the same accident. Even though contributory factors data are, up to a point, inevitably subjective; we can recognise that a driver's irresponsible behaviour may lead to driving errors both to the driver or even other users of the motorway. From the marginal effects, which are positive only for serious injury accidents, it can be concluded that when driving errors are involved, the possibility of slight and fatal injury accidents drop.

Figure 2 illustrates the observed and predicted values of the probabilities of an accident that occurred to be slight, serious or fatal, under the conditions that fatigue was involved or not (for HS accidents) and an HGV was involved or not (for MC accidents). The left set of bars shows the probabilities if the condition is true and the right if it is not.

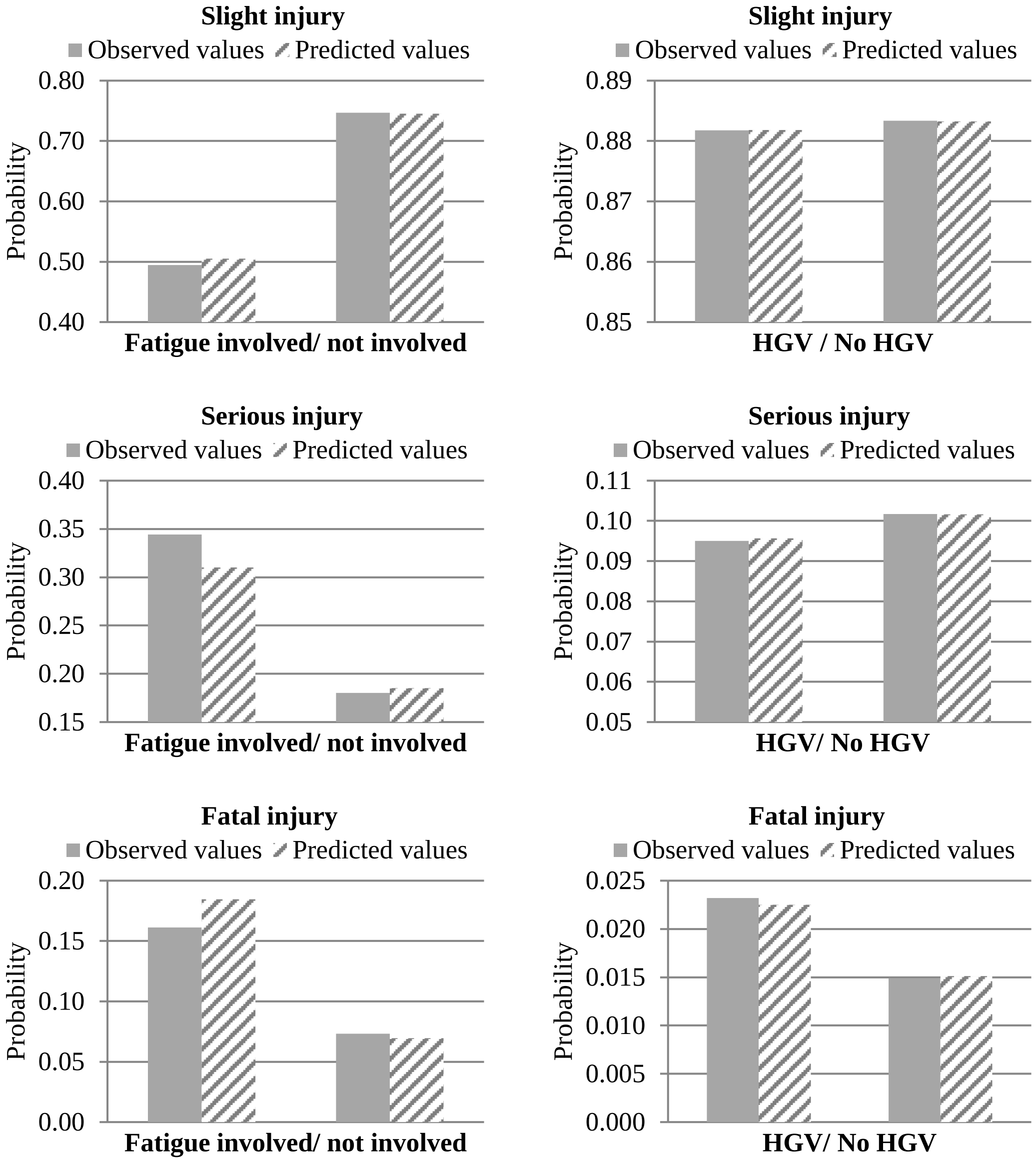

FIGURE 2 Observed and predicted probabilities for Contributory Factor 'Fatigue' (HS) and Heavy Goods Vehicle (MC) involved in the accident.

6. CONCLUSIONS

The motivation of this study was to extend research in the field of hard-shoulder accidents, as the severity of these accidents appears to be significantly higher. The aim was to identify any differences between the factors that contribute to the severity of HS and MC motorway accidents, using disaggregated accident data from motorways in England. Driver fatigue appears to be a much more common contributory factor for HS accidents, thus it was considered important to highlight its impact.

Severity of accidents is a discrete ordered variable and several models were examined in order to identify the most appropriate. The multilevel ordered logit model could have incorporated a second level that would represent any correlation among the accidents. In this study this level was counties, English geographical and administrative areas. However, it was estimated that the correlation among the motorway accidents in the same county was not strong enough to support the use of this model. In addition, the ordered logit model was also not suitable due to the violation of the parallel regression assumption; thus the generalised ordered logit model, which allows the relaxation of the assumption, was preferred.

Two models, one for MC and one for HS accidents were estimated and the results suggested substantial differences in the statistically significant variables. The variable with the highest impact for MC accidents was speed limit, which increases the severity. In addition, when an accident is single-vehicle, it is more likely for it to be fatal. Traffic volume was incorporated indirectly, which was one of the limitations of the study and it was estimated that during non-peak hours, the severity of MC accidents tends to increase. Dry surface conditions also have the same effect. On the contrary, left-hand-side drive vehicles and the presence of roadworks at the time of the accident, as well as good visibility, have a positive effect, giving more probabilities for a slight injury. According to the generalised ordered logit model, some of the variables may not have the same effect on all the categories of severity, which would not have been detected with the simple ordered logit model. For the MC accident model, several variables, such as HGV and the number of vehicles involved have two different coefficients, one for slight injury vs. serious and fatal and one for slight and serious vs. fatal injury. In terms of HS accidents, the number of significant variables is lower. Variables such as HGVs and fatigue are common for both models, but appear to have a much higher impact in this case. Fatigue also has a varying coefficient increasing even more the probability of a fatal accident when involved in a HS accident.

The limitations of this study are mainly related to data integrity. As mentioned, STATS19 accident data are collected by the police attending the accident scene and despite thorough training and special instructions provided, the data might be recorded subjectively; thus the contributory factors may not always be accurate. Furthermore, some proxies for risk factors (peak time and speed limits for traffic flow and speed) were used in this study. It would be of interest for future studies to further examine the effect of the actual traffic characteristics (e.g. flow and speed) on the HS and MC accident severity.

7. PRACTICAL APPLICATION

Considering that the level of severity of hard-shoulder accidents is five times higher than for the MC, the need for extra safety measures through informative campaigns and training should be considered. This study concludes that HGV drivers are a high risk group, especially for hard-shoulder accidents, and also fatigue appears to be a crucial factor. Therefore, it is important for the public sector or other related organisations to focus their safety campaigns to this specific group and especially raising the drivers' awareness of the hazards arising when using the nearside lane of the motorway. Professional drivers can also be targeted via their employers, while finding the gaps suggesting regular training. Lastly, private vehicle drivers can also be informed by campaigns that are focusing on the risks arising from tiredness.

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APPENDIX G – PAPER 2

A time-series analysis of motorway collisions in England considering road infrastructure, socio-demographics, traffic and weather characteristics

Full Reference

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Abstract

Traffic injuries on motorways are a public health problem worldwide. Collisions on motorways represent a high injury rate in comparison with the entire national network. Furthermore, collisions that occurred on the hard-shoulder are even more severe than those that happened on the main carriageway. The purpose of this paper is to explore motorway safety through the identification of patterns in the sequence of monthly hard-shoulder and main carriageway collisions separately over a long period of time (1993 to 2011) by using reported collision data from British motorways. In order to examine the trends of hard-shoulder and motorway collisions over the same period, a Vector Autoregressive (VAR) model is developed; this allows the inclusion of two time-series in the same model and the examination of the effect of one series on the other and vice-versa. Exogenous variables are also added in order to explore the long-term factors that might affect the occurrence of collisions. The factors considered were related to the infrastructure (e.g. length of motorways), socio-demographics (e.g. percentage of young drivers), traffic (e.g. percentage of vehicle-miles travelled by Heavy Goods Vehicles) and weather (e.g. precipitation). The results suggested different patterns in the sequences in terms of the lingering effects of preceding observations for the two time-series. In terms of the significance of exogenous variables, it is suggested that main carriageway collision frequency is affected by weather conditions and the presence of Heavy Goods Vehicles, while hard-shoulder collisions are decreased by the presence of Motorway Service Areas, which allow a safe exit off the motorway to stop and rest in case of fatigue.

Keywords*:* Public health, Motorway, Hard-Shoulder, Vector Autoregressive

Paper type: Published peer-reviewed journal

1. Background and Scope of the Study

Road traffic injuries have been an important global public health problem, being the eighth leading cause of death and the number one cause among those aged 15-29 years according to the World Health Organisation *(2013)*. Indicatively, from 2007 to 2010, there were approximately 1.3 million road traffic deaths worldwide each year. Specifically in Great Britain (GB), there were 183,670 casualties in 2013, of which 23,370 were killed or seriously injured casualties *(Department for Transport, 2014).*

Motorway collisions appear to have a much greater severity than the average of the national road network collisions in GB. This is reflected by higher fatal injury rates on the motorway network. Motorway collisions can be distinguished according to whether they occur on the hard-shoulder or not. The hard-shoulder is the lane on the verge (edge) of the road which, is only permitted be used for emergency purposes by the road users, for example in the case of a breakdown. Systematically though the lane is used by maintenance vehicles of motorway operatives and emergency vehicles (e.g. ambulances and police vehicles) *(Highway Code 2007)*. Sometimes those vehicles are obliged to remain on the hard-shoulder for a long period of time while the personnel are performing their tasks. Working on the hard-shoulder and roadside verges on motorways is therefore considered to be unsafe and risky. Data from GB suggest that a hard-shoulder (HS) collision is five times more possible to be fatal in comparison to collisions occurring on the main traffic lanes, also called the main carriageway (MC).

Exploring the potential long-term factors affecting the frequency of collisions on the motorway HS and MC can assist in formulating safety measures to reduce them. This way, it should also be possible to identify any differences between the two types of collisions that would lead to a different approach by safety professionals to prevent them. The goals of this analysis are to examine the motorway collisions over time and to investigate various control and exposure variables affecting such collisions that can potentially explain the evolution of the two different series.

The rest of the paper is organised as follows. Firstly, a review of literature on factors affecting motorway collisions and the statistical methods employed to investigate time-series data is presented. This is followed by the data collected for the HS and MC collisions. The section also looks at various descriptive statistics so as to find out facts about the sample data. Subsequently, the statistical method chosen to fulfil the objectives of this paper is presented, followed by discussion of the results from the statistical modelling. Finally, a summary of the research and some conclusions are drawn.

2. Literature Review

The purpose of this section is to identify some exposure and control variables that may affect motorway collisions and to explore the literature on the statistical methods employed in analysing time-series data, especially collision data.

2.1 Factors affecting motorway collision occurrences

Safety literature on motorway collisions spans several decades and is extremely rich. The factors that have appeared to affect road collision likelihood are generally divided into two categories: *engineering* and *human*.

Engineering factors are related to the *road infrastructure characteristics* and *traffic conditions,* as well as the *weather conditions*. The first category refers to attributes such as road curvature and lane width *(e.g. Haynes et al. 2007; Kononov et al. 2008)*. Traffic related conditions that primarily affect the collision occurrences are vehicle speed – which is further split in various forms such as average speed, speed variance and speed limit *(e.g. Elvik et al. 2004; Aarts and van Schagen 2006)* – as well as traffic flow and the composition of traffic, such as the percentage of Heavy Goods Vehicles (HGVs). Weather conditions also appear to be a quite significant factor in many aspects: precipitation (rain or snow), wind and fog *(e.g. Edwards 1994; Brijs, et al. 2008)*.

Human factors play a very important role in road collisions. The risk of being involved in a collision increases according to whether you fall into various driving groups. For example, HGVs drivers have been proved to be a high risk group *(e.g. Charbotel et al. 2002)*. Driver age too appears to be important as younger drivers are most commonly involved in collisions whether from inexperience, in-vehicle distraction or other reasons *(e.g. NHTSA 2008; Hassan and Abdel-Aty 2013)*. Gender has also been found to be important as male drivers generally are more often involved in collisions than females. It is further recognised that they are more prone to driving violations, and risky driving *(e.g. Evans 1991; Constantinou et al. 2011)*. Conversely, alcohol impairment is a common causal factor of collisions, especially the ones involving injury, amongst men and women *(e.g. Holubowycz 1994)*.

Driver fatigue appears to be one of the most often reported factors in road collisions, especially with HGV drivers *(e.g. Nordbakke and Sagberg 2007; Zhang and Chan 2014)*. On British motorways, drivers have been encouraged to take a break when feeling tired with the establishment of safety signs in the 1990’s by the then Highways Agency (now Highways England). These permanent messages read ‘Tiredness can kill – Take a break’ and are normally placed ahead of the Motorway Service Areas (MSAs). Their aim is to remind drivers to stop when necessary in safe areas and not in inappropriate places such as the HS *(Horne and Reyner 2001)*. The MSAs are government-approved facilities in the United Kingdom (UK) designed to provide a safe exit and rest areas for drivers using the motorway network *(Motorway Services Online 2015)*.

2.2 Statistical Methods for Modelling Time-Series Collision Data

Initial studies have focused on the development of a safety performance function based on traffic flow and density as predictors *(e.g. Cedar and Livneh 1982; Golob et al. 2003; Golob et al. 2004)*. Several studies have, however, concentrated on the application of advanced statistical techniques, including controlling for spatial dependency among adjacent segments, taking into account issues associated with nested collision data by employing multilevel modelling so as to reliably investigate the contributory factors (e.g. vehicles miles travelled, rainfall, precipitation, road geometry and other vehicle related factors) in explaining the variation in road collisions *(e.g. Jones et al. 1991; Miaou 1994; Shankar et al. 1996; Caliendo et al. 2007; Lord and Mannering 2010)*.

Most existing studies have focused on the total number of collisions that occurred on the motorways (highways/freeways) rather than distinguishing HS collisions from the MC collisions *(e.g. Shankar et al. 1996; Lord et al. 2005; Davis & Swenson 2006; Golob et al. 2008; Wang et al. 2009)*. Although the width of the HS has normally been employed as a predictor of motorway collision frequency *(e.g. Noland and Oh 2004)*, there is a dearth of literature on HS collisions and consequently, there is little known about the scale of safety occurrences on the HS.

A well-established choice for detecting patterns, trends and seasonality in a continuous time-series data set is the use of the Autoregressive Integrated Moving Average (ARIMA) model proposed by *Box and Jenkins (1976)*, which has been applied to model time-series count data in many applications over the last few decades including road collisions *(e.g. Zimring 1975; Houston and Richardson 2002; Goh 2005; Noland et al. 2008)*. Since road collisions are non-negative, integer and random event counts, *Karlis (2006)* argued that a classical ARIMA model may not be suitable in modelling time-series count data. However, *Quddus (2008)* pointed out that an ARIMA model performs well in dealing with aggregated time-series count data, especially when the mean of the count is relatively large.

Although modelling data sets for MC and HS collisions independently would reveal patterns, trends and seasonality of individual time-series, a way of combining and examining them together would appear more valuable. In terms of revealing the relationship between two time-series data sets, the cross-correlation function has been used in time-series modelling in various disciplines *(e.g. Haugh 1976; Lopez-Lozano et al. 2000; Pitfield 2005; Zebende and Filho 2009; Brockwell 2010; Zebende et al. 2011)*. For example, *Haugh (1976)* suggested the residual cross-correlation function which provides a means for testing the hypothesis that two stationary time series are independent *(Koch and Yang 1986; Duchesne et al. 2011)*.

An alternative method, which has had a long tradition as a tool for multiple time-series analysis is the Vector Autoregressive (VAR) models. *(e.g. Quenouille 1957)*. This method involves the simultaneous modelling of more than one time-series, while, it allows for exogenous variables to be included in the model (e.g. ***Lütkepohl*** *2005*). These variables can be related to and possibly explain the trends that the time-series follows. Several past studies have incorporate explanatory variables to investigate the correlation between road and driver characteristics as well as weather conditions and the frequency of road collisions *(e.g. Beenstock, 2000; Bergel-Hayat, 2013; Gomes, 2013; Theofilatos, 2014)*.

In this study, the time-series of HS collisions is examined separately from the MC in order to reveal any differences in the way they have evolved throughout the years. The VAR model would allow for the simultaneous modelling of the two series to investigate the possible effect on each other, while lags could be included. The addition of exogenous variables is necessary to include driver exposure to risk and to control for other factors that might be associated with the collisions, such as traffic or road related conditions. As risk on the HS might depend on the presence of HGVs travelling in the nearside lane, the study focuses on this group of drivers, along with the other exogenous variables. In addition, as the HS is often abused by drivers stopping for rest or other non-emergency reasons, the possible impact of the presence of the MSAs is investigated.

3. Collision Data Collection and Descriptive Statistics

National collision data for GB were obtained from the police, who have recorded details since 1985 of all road collisions in which one or more persons are killed or injured, and involved at least one motor vehicle using the STATS19 data collection system. The motorway collisions, including A-roads that have been upgraded to motorways, known as A(M) roads, are extracted and two sets of monthly time-series data are created according to where the first impact happened: collisions that occurred on the MC and collisions that happened on the HS of the motorways in GB from 1985 to 2011. Over these 27 years, a total of 199,388 injury collisions (in which 2.3% are fatal, 13.0% involve a serious injury and 84.7% involve a slight injury) occurred on the GB motorways of which 2% occurred on the HS. All tables and figures in this section were produced for this study using the STATS19 data, unless stated otherwise.

Figure 1 shows the monthly distribution of the reported road collisions for each of the two groups, MC and HS. They generally follow similar increasing/decreasing patterns from month to month. The lowest values for HS collisions are observed in April/May/June, while the highest are in November/December. MC collisions are mostly increased in October/November, while their lowest frequencies occur in January/February. The relative difference between the two extremes is approximately 25% for HS and 35% for MC collisions. Traffic and weather conditions are also fluctuating throughout the year; thus it needs to be examined whether they affect the collision monthly frequencies. The daily distribution during the week follows the same trend for both (peaks on Monday and Friday) and within a day both series exhibit similar patterns of hourly traffic flow with two defined peaks. In terms of types of vehicles involved in motorway collisions, a significant difference is observed in the rate of cars and HGVs between the two groups. More specifically, the percentages for HGVs involved in collisions are found to be 17.6% and 34.7% for the MC and the HS collisions respectively.

Table 1 shows the severity of collisions for each of the two groups. In the case of HS, the percentage of fatal injury collisions is almost five times higher than that of MC. The proportion of serious injury collisions is also relatively high in the case of HS collisions. It can therefore be stated that collisions on the HS are relatively more severe than those on the MC, which stresses the need for their investigation. A previous study *(Michalaki et al. 2015)* has shown that HGV involvement and fatigue tend to increase collision severity on the HS.

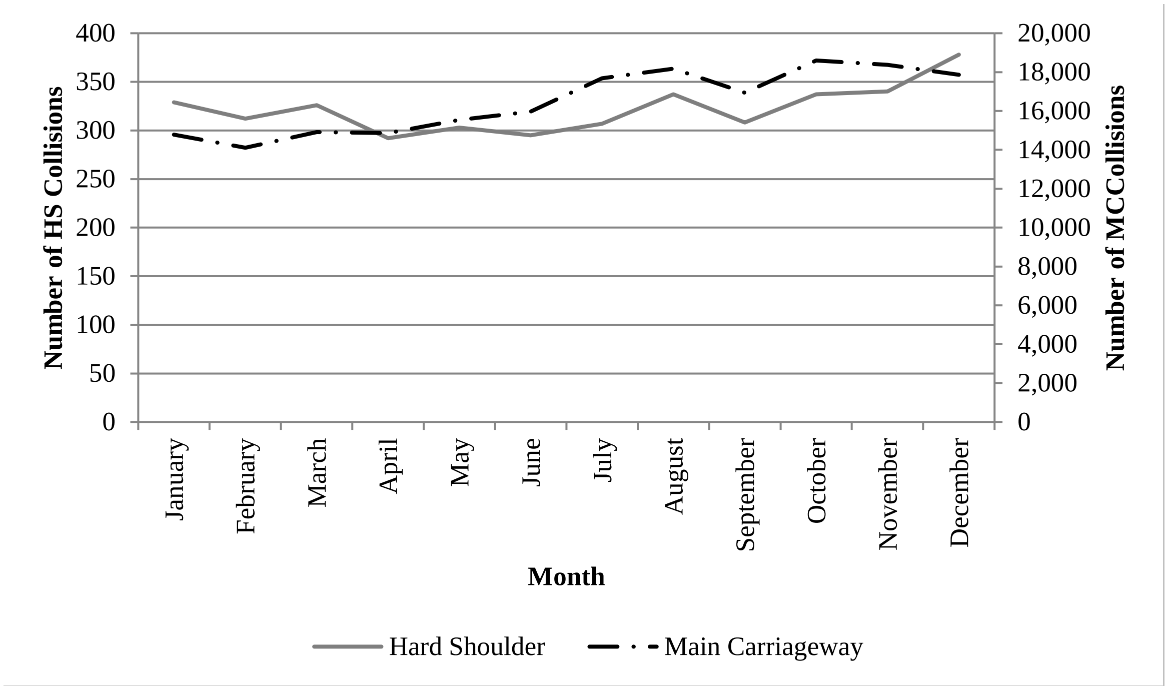

FIGURE 1 Monthly Distribution during the Year of the Number of Motorway Collisions on Hard-Shoulder and Main Carriageway in GB (1985-2011)

TABLE 1 Severity of Collisions on Motorways in Great Britain

Severity of Collision	***Hard-Shoulder Collisions (1985-2011)***		***Main Carriageway Collisions (1985-2011)***		***GB All Road Collisions (2011)***
	Frequency	Relative Frequency	Frequency	Relative Frequency	Relative Frequency
Fatal	391	10.7%	,647	2.3%	1.2%
Serious	912	25.0%	0,392	13.0%	13.8%
Slight	2,352	64.3%	33,595	84.7%	85.0%
Total	3,655	100%	57,634	100%	100%

In order to see whether there are trends and seasonality in the motorway collision data, two time-series plots are produced (Figure 2). They show strong seasonality for the MC collisions while there are both upward and downward trends. HS collisions steadily decrease over the study period.

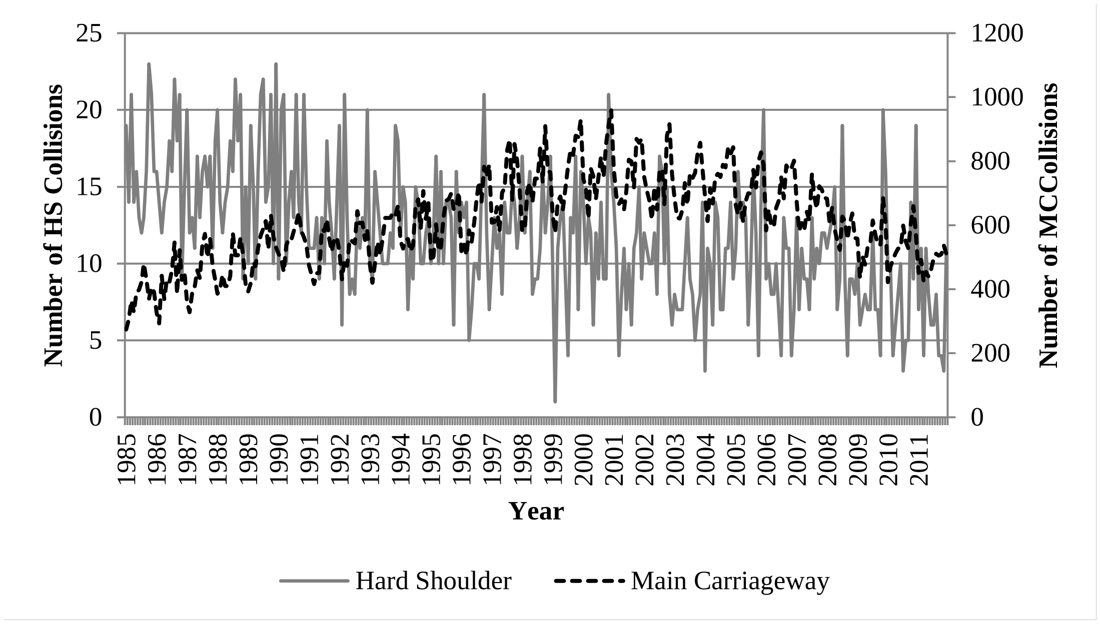

FIGURE 2 Evolution of the Number of Motorway Collisions on Hard-Shoulders and Main Carriageway per month in GB (1985-2011).

In addition to the endogenous (dependent) variables, which are the number of monthly collisions, data for exogenous variables that could possibly explain the variation of the collision frequency throughout the years are collected. These variables are related to the use of motorways, the infrastructure, vehicle and driver characteristics, as well as the weather conditions. However, the method of collection of historical traffic data on British motorways was changed in 1993. For consistency across variables, data are collected since from, or otherwise (see Table 2) from when these have become available. Their time interval is either a year or a month. The sources of these data were all available online: Department of Transport (DfT) in the UK, the UK Met Office, HM Treasury and Motorway Services Online. Table 2 provides the summary statistics for the exogenous variables and Figure 3 the trends of some for the years available.

Motorway traffic

- *Vehicle miles travelled (VMT)* on motorways in the UK by year in millions of vehicle miles travelled refer to the actual use of motorways by any type of vehicle and are used as a measurement of exposure of drivers to the risk of having a collision. A steady increase is observed from 1993 before becoming stable after 2006.
- *Percentage of miles travelled by HGVs* on motorways in England by year

It is of interest to investigate whether the presence of HGVs on motorways affects the likelihood of a collision, as they appear to be involved in a high percentage of motorway collisions, especially in the case of HS. This percentage has been decreasing since 1993 while a small peak is observed in 2010. It is noted that the absolute value of VMT by

HGVs has been increasing. However, the reduction of the percentage is perhaps due to a greater increase of VMT by other vehicles.

- *Percentage of cars exceeding the speed limit* on motorways in the UK (overall or by more than 10mph) by year

Contradictory results have been suggested regarding the relationship between speed of vehicles and collision likelihood. The speed limit in UK is normally 70mph (113 km/h). Cars exceeding the speed limit by more than 10mph (16km/h) are selected as an indicator of the driver's behaviour. Both percentages have been slowly decreasing since 2002 showing a general improvement in drivers' compliance.

Infrastructure characteristics

- *Motorway Service Areas (MSAs)* in the UK

These are the rest areas where drivers can leave the motorway. Since the first MSAs opened in 1959, new ones have been installed across the country. This variable is defined as the number of MSAs per 100 miles of motorways. There has been a 43% increase between 1993 and 2011.

- *Total length of motorways* in GB in miles by year

It is noted that the length of the HS is the same as that of MC, as all motorways, by definition, have an emergency lane. The width of HS is not included as a variable as it is generally following the British Standards and varies only when a Departure from Standards has been granted for physical or other reasons. There has been an 11% increase in the total length of British motorways between 1993 and 2011.

- *Road surface condition* in England by year

It is defined as the percentage of lane 1 length (next to the HS) surveyed requiring further investigation. This is stable from 2003 to 2008, when a significant decrease is noticed.

- *Public expenditure on transport* in the UK by year

The values were adjusted to 2012-13 price levels using Gross Domestic Product (GDP) deflators from the Office for National Statistics in the UK. There has been a fluctuation throughout the years of data collection.

Vehicle characteristics

- *Total number of vehicles* registered in the UK by year

The number of vehicles has been constantly increasing since the data has been collected (1994).

- *Average age of cars* registered in the UK by year

It represents the progression of technology in the car industry, which might be related to the reduction of motorway collisions. The average age increased from 1994 to 1997 and then again after 2004.

Drivers' characteristics

- Percentage of population per age group that hold a driving licence in the UK by year

- Percentage of trips in the UK by young drivers (aged from 17 to 29) by year
- Percentage of miles travelled per age group as a car/van driver by year

These variables are included to control for driver experience. The most representative variable is the one referring to the miles travelled; however, this information is only available since 2002. In the study, focus is on the miles travelled by young drivers. A drawback of this data is that the trips/miles do not only refer to motorways; however it is assumed is that they still capture the general level of experience of a driver.

Weather conditions

- Total precipitation in the GB in mm by month
- Average temperature in UK in Celsius degrees by month
- Total hours of sunshine in UK by month

Generally, according to previous studies *(e.g. Hermans et al. 2006; Caliendo, 2007),* a correlation between the increased collision frequency and either total precipitation, temperature or sunshine hours is expected. However, opposite results for the effect of precipitation have, to a smaller extent, also been suggested by others *(e.g. Karlaftis and Yannis, 2010; Bergel-Hayat, 2013).*

In the case of precipitation data, these were available for England + Wales (EW) and Scotland (SC) separately. Weighted average values were used according to the length of motorways, as in Scotland their lengths are limited in comparison to the rest of GB (England and Wales contain 87% of the total British motorway network).

TABLE 2 Summary statistics for the exogenous variables in the UK

Variable		***Period***	***Source***	***Obs.***	***Mean***	***Std. Dev.***	***Min***	***Max***
HS collisions (month)		1993-2011	STATS19	228	10.61	3.78	1	21
MC collisions (month)		1993-2011	STATS19	228	664.18	115.57	420	959
VMT motorways (millions)		1993-2011	DfT, Traffic	228	55.68	6.37	42.4	62.5
% VMT by HGVs on motorways		1993-2011	DfT, Traffic	228	12.67	0.58	11.4	13.3
% cars exceeding speed limit		2002-2011	DfT, Speed	120	52.80	2.90	49	57
% cars exceeding speed limit by more than 10mph		2002-2011	DfT, Speed	120	16.90	2.22	13	20
Motorway Service Areas (# per 100 miles of motorways)		1993-2011	Motorway Services Online	228	4.98	0.42	3.86	5.50
Total length of motorways (miles)		1993-2011	DfT, Road lengths	228	2144.32	71.10	1995	2218
Road surface condition (%)		2003-2011	DfT, Road condition	108	5.12	0.78	3.65	5.88
Public expenditure on transport (£m)		1993-2011	HM Treasury	228	17.59	4.51	10.60	24.50
Number of vehicles		1994-2011	DfT, Vehicles	216	30458.86	3141.84	25231	34228
Average age of cars (year)		1994-2011	DfT, Vehicles	216	6.92	0.25	6.61	7.54
% Driving licence holders aged	from 17 to 20	1993-2011	DfT, National Travel Survey (NTS)	228	36.74	5.56	27	47
	from 21 to 29			228	69.05	4.40	63	75
	from 30 to 39			228	82.32	1.63	78	85
	from 40 to 49			228	83.11	1.07	81	85
	from 50 to 59			228	79.95	2.77	75	83
	from 60 to 69			228	71.26	5.94	61	80
	over 70			228	45.95	7.07	35	59
% Trips by young drivers (under 29)		1995-2011	DfT, NTS	204	0.14	0.02	0.11	0.17
% VMT by young drivers (under 29)		2002-2011	DfT, NTS	120	0.19	0.01	0.17	0.20
Precipitation (mm)		1993-2011	Met Office	228	84.55	36.96	11.94	198.89
Temperature (^{0}C)		1993-2011	Met Office	228	9.10	4.32	-0.90	17.80
Sunshine (hours per month)		1993-2011	Met Office	228	116.80	54.95	20.50	253.30

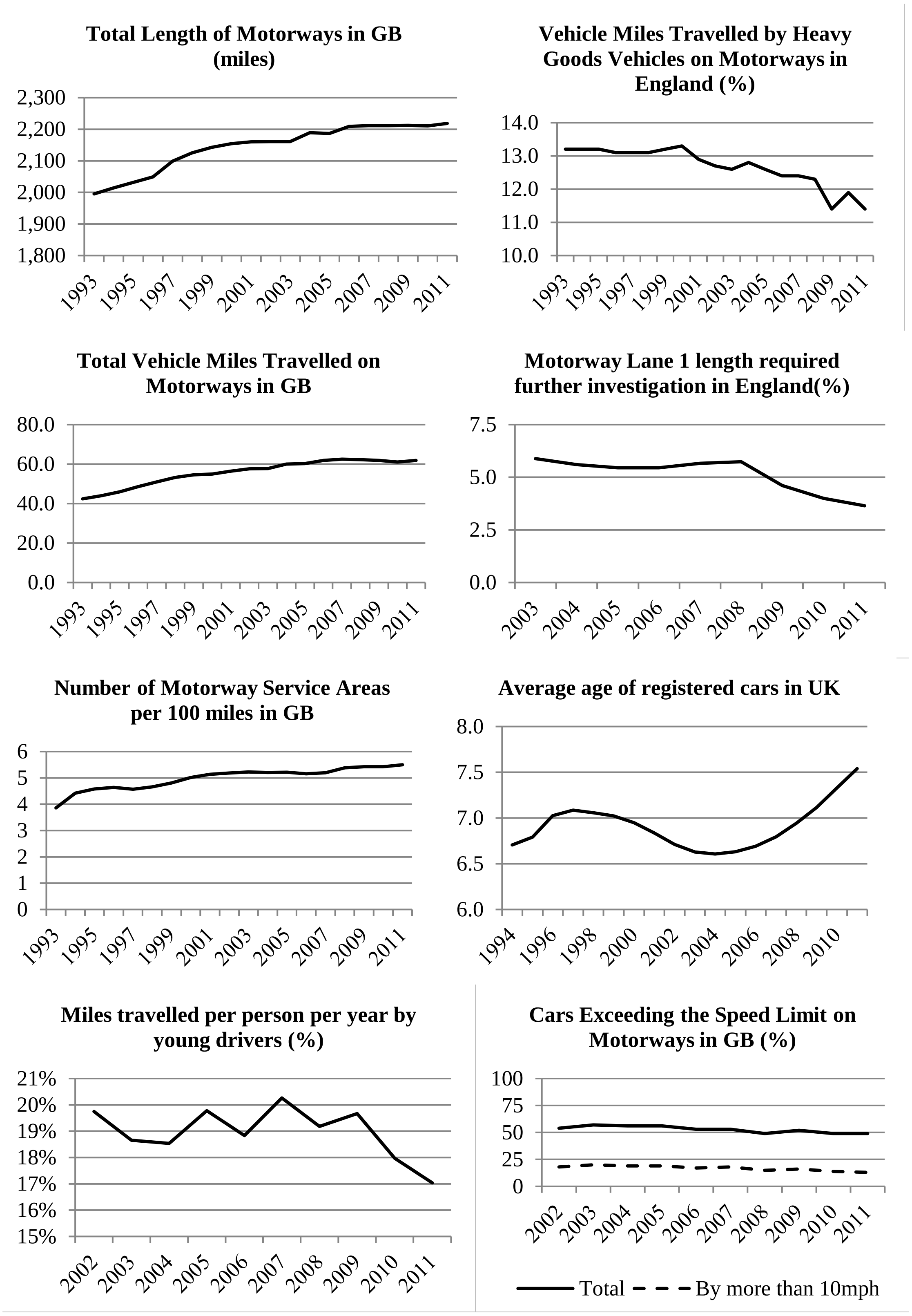

FIGURE 3 Trends of exogenous variables for the years available

4. Time-Series Statistical Modelling using the Vector Autoregression Analysis

The objectives of the study are to examine the relationship between the frequency of HS and MC collisions over time and to relate their frequencies to exogenous factors. Therefore, a statistical model that addresses both objectives must be selected. As discussed in

Section 2.2, the Vector Autoregression (VAR) model can simultaneously analyse the relationship between two time-series datasets, while its variation, termed VAR(X), allows the inclusion of exogenous variables. In this section, attributes of this model and its suitability for this study are discussed.

The stationarity of a time-series is an assumption commonly required in statistical models. When a stochastic process is stationary, the statistical properties of the process are not a function of time *(Box and Jenkings, 1976).* Besides reducing the mathematical complexity of a stochastic model, the stationarity assumption may reflect reality. In certain situations, though, the statistical characteristics of a process are a function of time – known as a non-stationary series. To model an observed time series that possesses non-stationarity, a common procedure is to first remove the non-stationarity by invoking a suitable transformation – such as using the differences (regular, seasonal or both) of the original series – and then to fit a stationary stochastic model to the transformed sequence *(Box and Jenkings, 1976).* An advantage of developing a VAR model in opposition to other time-series modelling methods is that the stationarity assumption of time series data set is not mandatory *(Canova, 2007).*

Cointegration of the dependent variables – in this study the number of collisions on the HS and MC – needs to be tested. This would indicate any linear relationship among them and thus that the VAR specification would not be the most suitable representation. If there is at least one cointegration equation, a different version of the model should be applied, known as the Vector Error Correction (VEC) model which contains the cointegration relations. For this check, the Johansen's test may be used *(Johansen, 1991).*

The VAR model fits a multivariate time-series regression of each dependent variable on lags of itself and on lags of all the other dependent variables. The lags are treated as explanatory variables. A variant of the VAR model can also be used to allow the inclusion of exogenous variables in the regression to possibly explain the evolution of the dependent ones, known as VAR(X). These two characteristics of the VAR model suit the objectives of this study as the time-series collisions on the HS and MC can be included in the same model along with all the engineering and human factors that possibly affect their occurrence. A VAR model is easy to use and interpret *(Watson 1994).* The analysis typically proceeds by specifying and estimating a model and then checking for its adequacy. Model revisions are performed until a satisfactory model has been found.

The VAR(p) model with exogenous variables is written as (Lütkepohl 2005):

$$\mathrm{y_t = AY_{t-1} + Bx_t + u_t}$$

Where:

p is the number of lags,

K is the number of endogenous variables

M is the number of exogenous variables

y_t is the vector of endogenous variables (the length of vector is K),

A is a K × K·p matrix of coefficients,

B is a K × M matrix of coefficients

x_t is the vector of exogenous variables (the length of vector is M)

u_t is the vector of white noise innovations (the length of vector is K)

Y_{t-1} is the vector given by $Y_{t-1} = \begin{pmatrix} y_{t-1} \\ \vdots \\ y_{t-p} \end{pmatrix}$. The length of vector is K·p and is formed by stacking the y_t vectors for all the lags.

Intercept terms in the model are included in the x_t. The coefficients are estimated by iterated seemingly unrelated regression, a three-stage least squares (3SLS) method *(*see *Zellner and Theil, 1962; Weesie, 1999).*

Since the restriction of stationarity is not imposed before applying the model, the residuals of the models are checked for non-stationarity. Firstly, the residuals are plotted in order to identify any patterns *(Canova, 2007)*. In addition, the Lagrange multiplier (LM) test for autocorrelation in the residuals resulting from the VAR model can be employed *(Johansen, 2005)* in the postestimation phase. The null hypothesis is that there is no autocorrelation between the residuals.

In order to investigate whether one series can cause the other the Granger causality test can be employed. A variable *x* is said to Granger-cause a variable *y* if, given the past values of *y*, the past values of *x* are useful for predicting *y (Granger, 1969)*. A common method for testing Granger causality of variable *x* on variable *y* is to test the null hypothesis that the estimated coefficients on the lagged values of *x* are jointly zero, using Wald tests. Failure to reject the null hypothesis is equivalent to failing to reject the hypothesis that *x* does not Granger-cause *y*.

5. Estimation Results of the VAR(X) Model and Discussion

Two time-series of aggregated data (i.e. all motorways in GB) are formed: the monthly number of collisions that occurred on the motorway HS in GB and the monthly number of collisions that occurred on the motorway MC in GB over the same period of time. Different time-series collision models are developed using the VAR(X) method, as described in Section 4, for HS and MC collisions in order to identify the 'best-fitted' collision model. Exogenous variables are included for the time period that data are available.

5.1 Lag selection and cointegration

In order to apply the VAR and VAR(X) models, the number of lags included needs to be selected and cointegration between the series needs to be tested. In the preestimation phase, a set of model criteria are estimated without any exogenous variables. This is applied for each of the models, including lags up to 12. In addition, the existence of the cointegration equation is tested for several forms of the dependent variables, such as the number of MC and HS collisions, their natural logarithms and their first and seasonal differences. Based on the final prediction error (FPE) (***Lütkepohl, 2005)***, Akaike's Information Criterion (AIC) *(Akaike 1973; 1974)*, Hannan and Quinn Information Criterion (HQIC) *(Hannan and Quinn, 1979),* 12 lags should be included in the model for all cases of dependent variables. Only the Bayesian Information Criterion (BIC) *(Schwarz, 1978)* suggests the use of 2 lags. Indicatively, Table 3 shows the results of the tests for the VAR model where two dependent variables are included; the logarithms of HS and MC collisions (years 1993 to 2011). When the natural logarithms of the dependent variables are taken and 12 lags are included, there are no cointegration equations; suggesting that the VAR model can be used, while the stationarity of residuals is tested at the end.

TABLE 3 Model Fit Statistics for the VAR model including the logarithms of Hard-Shoulder and Main Carriageway collisions (data from 1993 to 2011).

Lag	*FPE*	*AIC*	*HQIC*	*SBIC*
0	0.0052	0.4185	0.4312	0.4498
1	0.0021	-0.5104	-0.4725	-0.4166
2	0.0021	-0.5119	-0.4488	-0.3556*
3	0.0021	-0.4822	-0.3938	-0.2635
4	0.0021	-0.4806	-0.3669	-0.1993
5	0.0022	-0.4638	-0.3249	-0.1201
6	0.0022	-0.4423	-0.2782	-0.0360
7	0.0020	-0.5317	-0.3423	-0.0629
8	0.0019	-0.5839	-0.3692	-0.0526
9	0.0019	-0.5725	-0.3326	-0.0213
10	0.0018	-0.6616	-0.3964	-0.0053
11	0.0016	-0.7704	-0.4800	-0.0516
12	.00137*	-0.9166*	-0.6010*	-0.1353

5.2 Results of VAR(X) model

Table 4 shows the results for the VAR(X) model for the MC and HS motorway collisions using data from 1993 to 2011, as allowed by the exogenous variables availability. Since some of these variables were available for an even shorter period of time, models including variables available since 2003 were also tested; however a more suitable model was not indicated. Due to autocorrelation between the residuals, some of the lags were excluded from the model.

TABLE 4 Results of VAR(X) model for motorway collisions (1993-2011)

Vector Autoregression				
Sample	1993-2011			
Equation	**MC collisions**		**HS collisions**	
Variable	**Coef.**	**z**	**Coef.**	**z**
Lags				
Log (MC collisions)				
Lag 1	0.223	***4.120***	0.173	0.550
Lag 2	0.139	***2.750***	0.178	0.610
Lag 4	0.108	***2.010***	-0.581	***-1.880***
Lag 5	0.043	0.810	0.254	0.820
Lag 6	-0.102	***-2.070***	0.457	1.610
Lag 9	-0.131	***-2.490***	-0.175	-0.570
Lag 11	0.147	***2.950***	-0.440	-1.520
Lag 12	0.467	***8.720***	0.596	***1.920***
Log (HS collisions)				
Lag 1	0.009	0.770	0.039	0.570

Lag 2	-0.280	***-2.360***	-0.088	-1.260
Lag 4	-0.016	-1.300	0.108	1.530
Lag 5	-0.042	***-3.470***	-0.004	-0.050
Lag 6	-0.025	***-1.970***	0.021	0.290
Lag 9	-0.006	-0.510	0.009	0.120
Lag 11	-0.017	-1.380	0.001	0.020
Lag 12	-0.001	-0.050	-0.046	-0.660
Exogenous variables				
% VMT by HGV on Motorways	0.063	***2.540***	-0.002	-0.020
Precipitation	0.001	***5.760***	0.001	0.820
Sunshine	0.001	***5.400***	0.000	-0.450
Motorway Services	-0.047	-1.240	-0.369	***-1.660***
Constant	0.233	0.800	1.060	0.630
Equation	RMSE	R-sq	chi2	P>chi2
Log (MC collisions)	0.06913	0.8596	1322.375	0.0000
Log (HS collisions)	0.40017	0.1977	53.238	0.0001
Parameters: 21				
Model Fit Statistics				
Log likelihood	188.371			
FPE	0.00089			
AIC	-1.35528			
HQIC	-1.09014			
SBIC	-0.69898			
No of observations: 216				

The residuals of the model estimated are then tested for stationarity to check whether a way to control non-stationarity should have been taken into consideration. The residuals of the two series are plotted along with the 1-lag and 12-lag residuals (Figures 4 and 5). Since no correlation pattern is observed, the choice of this VAR model appears to be valid.

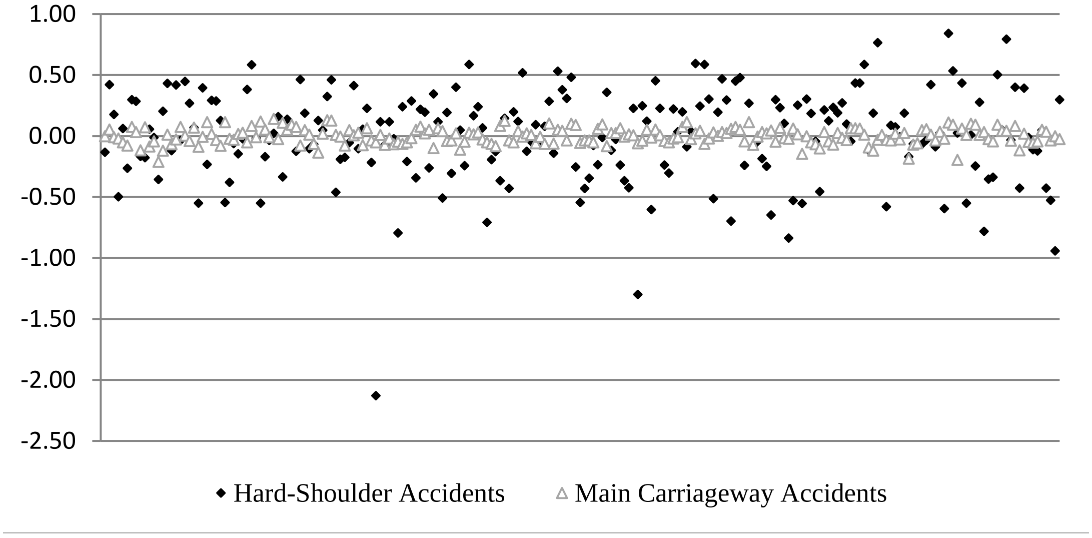

FIGURE 4 Residuals of the VAR model for the Hard-Shoulder and Main Carriageway collisions equations

For further confirmation of validity, the Lagrange-multiplier test is used (Table 5). The null hypothesis of no autocorrelation cannot be rejected at a 90% level, suggesting no misspecification of the model.

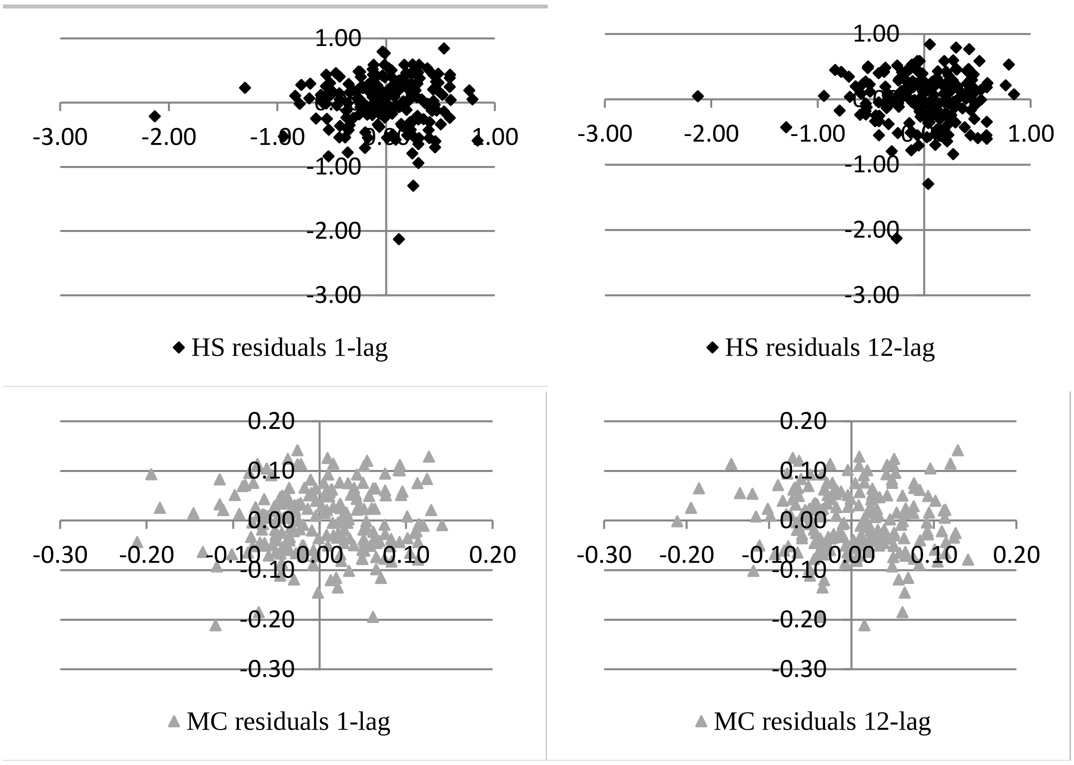

FIGURE 5 Relationship of residuals of the VAR model for the Hard-Shoulder and Main Carriageway collisions equations with lagged residuals

TABLE 5 Lagrange-multiplier test results for VAR(X) model

lag	chi2	df	prob>chi2
1	2.8678	4	0.58019
2	1.3234	4	0.85740
3	1.6214	4	0.80495
4	5.1672	4	0.27057
5	4.2478	4	0.37351
6	1.9376	4	0.74724
7	4.4969	4	0.34292
8	5.7976	4	0.21478
9	2.7492	4	0.60063
10	2.0303	4	0.73018
11	8.1139	4	0.08749
12	3.5578	4	0.46915

5.3 Discussion

The first part of the results (*'**Lags**'*) shows the relationship between the number of MC and HS collisions and the previous values of the same series (monthly lags) up to one year (lag 12). In addition, it presents the relationships of MC collisions with the lags of HS collisions and vice versa. From Table 4, it is noticed that there are differences in which lags are significant across the two equations.

The coefficient value for the MC in relation to lag 1 of MC collisions (MC-MC) is +0.223, while to lag 12 is +0.467, showing a positive relationship between the values of a month with the month before and the corresponding one of the previous year. This suggests that there is monthly and annual seasonality in MC collisions. In addition, a negative relationship is expected between current values and values 6 months later, as the MC-MC coefficient at lag 6 is –0.102 (z = –2.070). Accordingly, seasonality in the HS series (HS-HS) is not apparent in this model, as none of the coefficients are significant.

The simultaneous modelling of the two-series provides the opportunity to relate the current values of one series to the lags of the other. As it is shown in the MC equation, several coefficients of the HS lags are statistically significant; more specifically lags 2, 5 and 6. For instance, the value of lag 6 coefficient for MC-HS is –0.025, showing a negative relationship between the current values of MC collisions and the values of HS collisions six months before. The same applies in the other equation, in the case of HS collisions as the dependent variable, where the value of lag 12 coefficient for HS-MC is +0.596. This suggests that when the values of MC collisions have increased, the values of HS collisions in a year's time will also increase, although this does not imply any cause-causality relationship.

The Granger test results (Table 6) suggest that for the MC collisions, the null hypothesis can be rejected; thus, the coefficients of the lags of HS collisions are not jointly zero and would be useful for MC collision prediction. On the contrary, MC collisions do not seem to be useful for the HS collisions' equation, as the null hypothesis cannot be rejected. This also supports that the evolution of HS collisions does not have a strong relationship with MC collisions, showing that the two series have to be examined separately.

TABLE 6 Granger causality Wald tests for VAR(X) model

Equation	Excluded	chi2	df	Prob>chi2
Log (MC collisions)	Log (HS collisions)	25.335	8	0.001
Log (MC collisions)	ALL	25.335	8	0.001
Log (HS collisions)	Log (MC collisions)	12.213	8	0.142
Log (HS collisions)	ALL	12.213	8	0.142

Out of all the exogenous variables investigated in this model ('***Exogenous variables***'), some appear to be significant in the equation of MC collisions and one of them for the HS collisions. The proportion of vehicle miles travelled by HGVs on motorways appears to have a positive relationship with the evolution of collisions confirmed by the positive coefficient and statistically significant value (+0.057). This finding is in line with other existing studies *(e.g. Charbotel et al. 2002).* Due to multi-collinearity, the proportion of HGVs could not be included in the model along with the total vehicle miles travelled.

Regarding the weather conditions, it is argued that both precipitation and hours of sunshine per month increase the number of MC collisions. As in other studies *(e.g. Antoniou 2013),* it is also supported here that rainfall and snow are associated with a higher number of collisions. In addition, the hours of sunshine per month appears to have a positive relationship with the number of MC collisions, as has been suggested in other studies *(Hermans, 2006).* Under rain conditions, lower visibility is expected as well as a higher risk of skidding/losing control of the vehicle. On the other hand, sunny weather can be linked with a higher likelihood of glaring, especially on the motorway. It could also be suggested that, from a behavioural point of view, drivers become less careful and concentrate less when the conditions on the road appear good.

Motorway Service Areas appear to be a significant factor for HS collisions, having a negative relationship at the 90% confidence level. This indicates the importance for the drivers to be able to exit the motorway safely and take any preventative action required when tired. In addition, it has been observed that drivers do stop on the HS for non-emergency reasons as to check directions or make a phone call. The presence of MSAs on the motorway, including the frequent signage that indicates the distances to the next ones, discourages the drivers from stopping on the HS – unless there is an unexpected emergency – reducing the exposure of stopped vehicles to live traffic. It would be of interest to examine how the use of MSAs by the road users has evolved throughout the years, but these data were not available. In addition, as fatigue is an important factor of motorway collisions *(Michalaki et al. 2015),* drivers are encouraged to have a break at the MSAs when feeling too tired to continue their journey. This is supporting Horne and Reyner's work *(2001)* to establish signs on motorways to encourage the use of rest areas when required.

6. Conclusions

This paper focused on a major public health problem; that of motorway collisions. A special interest was shown in the road collisions that occur on the emergency lanes of motorways – the hard-shoulder (HS). Using 27 years of monthly collision data from Great Britain, it was found that HS collisions are much more severe than main carriageway (MC) collisions (10.7% of HS collisions are fatal vs. 2.3% of MC collisions being fatal). The time-series plots provided information in terms of trend and seasonality, showing evident differences. After having better information on the data by employing descriptive statistics, time-series modelling was applied, and more specifically the Vector Autoregressive Analysis. The advantage of the VAR model is providing a way of examining the joint evolution of two time-series that are not expected to progress in isolation.

Firstly, the model, which included 12 monthly lags as explanatory variables, suggested that the relationship between the two series is not strong. In order to investigate the factors that could be related to the number of collisions, exogenous variables were also incorporated. However, due to limitations in data availability, smaller dataset was used (1993-2011). Exogenous variables that appeared to be significant in the VAR model for the MC collisions were related to the HGVs travelling on motorways, as well as the weather conditions –

especially precipitation and hours of sunshine – while the presence of Motorway Service Areas (MSAs) was significant for HS collisions.

The reduction of the percentage of VMT travelled by HGVs – which does not imply a reduction in the absolute number of VMT travelled by HGVs as well – decreases the collision frequency, showing that the composition of traffic is important in motorway safety. Increasing awareness of HGV drivers regarding the safety concerns that they should have in the environment they are working through training could be crucial as they appear to be a high risk group. For future study, it would be interesting to also investigate how the age of HGVs affects the likelihood of collisions, as well as finding more measures, apart from exceeding the speed limit, for drivers' compliance to the driving rules. Furthermore, the results suggested that the presence of rest areas (known as Motorway Service Areas) has a positive effect in the reduction of motorway collisions. These areas have had a significantly increased presence on British motorways in the last decades. Their further spread is recommended, especially in geographical areas where they are not as common. In addition, all drivers – of private vehicles and HGVs – should be encouraged to use them whenever they feel tiredness during their journey or need to perform any other non-emergency task.

A multitude of private vehicles and operatives use the HS regularly for emergency or other reasons (e.g. road maintenance) and they are constantly in danger when stopped in these positions. Collisions on hard-shoulders, even though their frequency is low, have serious impacts when they occur. This research supports that while devising motorway safety systems and strategy it is important that collisions on the hard-shoulder are examined separately in order to be able to provide specific solutions for preventing them. Such solutions could be campaigns to promote only the appropriate use of the hard-shoulder and use of service areas on the motorway, as well as preventing road users from stopping at this lane when not in an emergency.

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APPENDIX H – PAPER 3

A sensor-based system for monitoring hard-shoulder incursions: review of technologies and selection criteria

Full Reference

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Abstract

According to safety observations from motorway operators in the United Kingdom, the hard-shoulder is occasionally violated by road users travelling in the nearside lane. These unintentional movements (hard-shoulder incursions) can impose risk to operatives performing activities on the network. To further investigate these events, a sensor-based system can be used for monitoring them and collecting related data such as severity of incursion and vehicle classification. A review of vehicle detection technologies that could be applied for this purpose is presented, along with the criteria for selection of the most suitable technology and implementation sites. Two potential non-intrusive systems are also described, a laser- and a radar-based systems, which provide different levels of flexibility and data.

Keywords: hard-shoulder incursion, vehicle detection, monitoring system, radar sensor, laser sensor

Paper type: Published conference paper

1 Introduction

The hard-shoulder of a motorway is normally used by the public in the event of an emergency or by emergency services as a through route to incidents. The hard-shoulder is also used for operation and maintenance activities. Thus, vehicles of motorway operators often remain on this lane for short durations whilst personnel perform work under live traffic conditions. Even though interest has been raised on the risk of having an accident on the hard-shoulder [1-7], this has not been investigated through rigorous research.

Safety observations from motorway operators in the UK have shown that vehicles travelling on the nearside lane of the main carriageway on occasion violate the hard-shoulder (Fig. 1). Considering that this could occur at any time an operator or emergency vehicle is on the hard-shoulder, it is important to investigate and further understand these events in order to reduce exposure under high-risk conditions. The aim of this study is to review the existing technologies that could be used to track hard-shoulder incursions and the criteria used for the selection of a system for this purpose.

To collect data of hard-shoulder incursions, a system installed on the network would need to fulfil the following goals: detecting, measuring, identifying and recording/storing incursion-related data.

- ***Detecting***: The system needs to detect the violations of the raised rib edge-line of the main carriageway (commonly referred to as 'rib-line'), which is the line separating the hard-shoulder from the adjacent nearside running lane. These violations are caused by vehicles that are not positioned in the middle of the lane and move onto the hard-shoulder while crossing the rib line. These violations are considered to be inadvertent, unless the road user intends to stop on the hard-shoulder in the case of an emergency or vehicle breakdown.
- ***Measuring***: While detecting hard-shoulder incursions, the system should also measure the severity of incursion, which can be defined by the width (D) and the length (L) of the violation (Fig. 2). The width of an incursion represents how far over the rib-line the vehicle has transgressed. Having the trajectory of the vehicle could provide this information, as well as the length which the vehicle travelled over the rib-line.
- ***Identifying***: In order to explore high risk driver groups, these incursions need to be linked to the identity of the vehicle, i.e. the classification of the vehicle and its speed. The classification of the vehicles is in two main categories (e.g. car or truck) or in multiple categories (e.g. car, van, bus, small truck, large truck, transporter or caravan). There are several methods of classifying vehicles, such as number of axles and space between them, total length/ size of the vehicle and vehicle weight. The speed of the vehicle, according to the technology used, might be directly measured or estimated.
- ***Recording and storing***: Finally, all raw data received by the system must be recorded and stored to be readily available for further review and analysis.

Figure 1. Hard-shoulder incursion of a truck on the motorway (slight/serious). (Source: P. Michalaki)

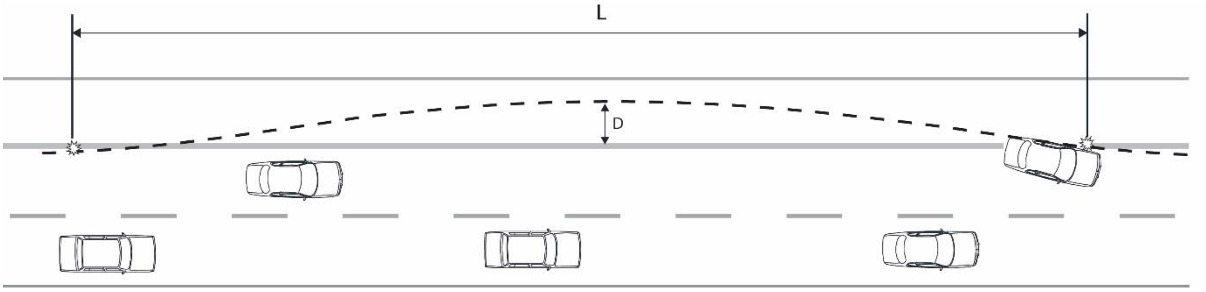

Figure 2. An illustration of a hard-shoulder incursion. (Source: P. Michalaki)

2 Review of Technologies

In this section, potential sensor-based technological solutions for setting up a hard-shoulder incursions monitoring system are discussed, along with the advantages/disadvantages of each (Table 1).

2.1 Intrusive and non-intrusive technologies: advantages and limitations

The main categorisation of vehicle detection and traffic counting technologies is in two groups: *intrusive* and *non-intrusive* devices. The distinction is based on the level of disruption to normal traffic and the road, as well as the risk to the operator while installing, operating and maintaining the equipment. By definition, non-intrusive devices do not require installation in or on the road. Thus, intrusive devices tend to be permanently installed, while non-intrusive are preferable in temporary, short-term surveys. Both types of technology present several advantages and drawbacks. According to the purpose of the survey, the conditions under which this is performed and the requirements of the motorway operator, it can be decided which device would be most appropriate. Some aspects of these devices are discussed below:

- ***Safety***: Safety of road workers and the public is a key priority. As there is little or no direct interaction with live traffic, non-intrusive devices are generally safer to install. In addition, as the pavement is not disrupted, the carriageway is not adversely affected. However, over-roadway sensors in specific, which are mounted over traffic lanes, can disrupt traffic and pose a safety risk to the installers as the installation may require for vehicles to be parked on the road.
- ***Security***: A concern for non-intrusive devices is security. As they can be installed at the side of the carriageway, they are exposed to risk of accidental damage or vandalism. To secure the equipment against damage or theft, the operator must keep workers informed and updated about the presence and scope of the equipment as well as protect it against theft.
- ***Portability***: Due to the way intrusive devices are fixed on a network (e.g. under the pavement), they do not allow for easy transfer from site to site, which may be a requirement especially due to cost constraints, while non-intrusive can be more flexible.
- ***Cost***: Due to traffic management and increased labour, the cost of installing intrusive devices is generally higher. In addition, due to the lack of portability, the amount of locations where the devices can be permanently fixed is reduced.
- ***Environmental conditions***: Both intrusive and non-intrusive devices can be affected by environmental conditions, though not always in the same way. Thus, intrusive devices, such as piezo-electric cable, are more sensitive to wet road conditions, as well as snow and frost. On the contrary, non-intrusive devices, such as cameras, tend to be affected by low visibility (e.g. fog).

2.2 Examples of intrusive technologies

2.2.1 Inductive loops

Inductive loops are one of the most common vehicle detection and traffic counting methods used worldwide [8]. An inductive loop system consists of a cable, which is embedded into or under the roadway in a roughly square configuration, a cable extension and a counting device placed on the side of the road [9, 10]. The loop is based on the principle that a magnetic field introduced near an electrical conductor causes an electrical current to be induced. A metal vehicle passing over the loop acts as the magnetic field and the inductive loop as the electrical conductor [10]. The data supplied by conventional inductive loop detectors are vehicle presence, classification, count and occupancy. Loops cannot directly measure speed; however this can be estimated using a difference loop configuration [11].

Advantages of the inductive loops are its well-known and understood operation as it is mature technology. Also, the equipment cost is relatively low in comparison to other sensor technologies. The same does not apply though to the life-cycle cost of the sensors, as the installation cost is significant. Also, the installation and repair require disruption of traffic and the carriageway pavement. The wire loops are also subject to the stresses of traffic and temperature [8]. In addition, for this study a new configuration would need to be set up, as the existing loops in their normal set-up would not be able to detect incursions.

Table 1. Advantages and disadvantages of sensor devices.

Technology		Advantages	Disadvantages
Intrusive	inductive loop	Well established technology. Insensitive to weather. Low cost.	Does not provide information on the exact position of the vehicle
	pneumatic road tube	Low acquisition cost. Easy to install.	May be displaced resulting in loss of data. Snow can damage road tubes. If installed in a perpendicular direction to the traffic, the severity of HS incursion cannot be measured. A parallel installation is examined as an alternative.
	bending plate	High acquisition cost	Requires working within the traffic lane and is time consuming
	piezo-electric sensor	It counts weight and speed.	Does not provide information on the exact position of the vehicle. Requires working within the traffic lane and is time consuming. If placed on road surface, may be displaced resulting in loss of data
Non-intrusive	magnetic	Insensitive to weather. Ease of deployment.	Difficulty in discriminating longitudinal separation between closely spaced vehicles
	infrared	Accurate measurement of vehicle position and speed. Multiple lane operation available	Operation may be affected by low visibility. Installation and maintenance require lane closure. Requires regular maintenance. High cost.
	radar	Insensitive to weather. Collects all the data required	High cost
	ultrasonic	Low cost	It can be affected by environmental conditions
	video image processing	Easy to add and modify detection zones	Performance affected by inclement weather. Reliable night-time signal actuation requires street lighting

2.2.2 Pneumatic tubes

Pneumatic road tube technology uses hollow rubber tubes to detect vehicles by the change in air pressure generated when a vehicle tyre (or one axle) passes over a tube [12, 13]. The road tube is normally installed across traffic lanes, perpendicular to the traffic flow direction [11]. A device is placed at the side of the road and while connected to the tubes, it records the vehicle axles by the change in pressure. When activated, the device notes the time of the event

[12, 13]. The pneumatic road tube sensor is portable, using rechargeable batteries as a power source [11].

There are several road tube configurations that can be used by a counter depending on the number of lanes and the data needs [12]. Axle counts can be converted to count, speed, and/or classification depending on how the configuration is structured [13]. Looking at the pattern of the compression times (for instance, the time interval between two activations of the counter caused by a vehicle's axles), each compression event is matched to a specific vehicle based on a set vehicle classification scheme. Two tubes attached to the same counter placed a set distance apart on the carriageway can determine the vehicle speed by measuring the time interval between an axle hitting the first and second tubes.

Advantages of pneumatic tube sensors are the low power consumption and the quick installation; this however, requires some intrusion into the flow of traffic [13, 14]. Road tube sensors are usually low cost and simple to maintain. Sensor manufacturers often supply software packages to assist with data analysis. Disadvantages include limited lane coverage and inaccurate axle counting when multiple axle vehicles' volumes are high or when vehicles are travelling at low speed and/or high proximity. Also, accuracy is subject to weather and temperature conditions [10, 11, 12].

For this study, the tubes could either be installed on the hard-shoulder perpendicularly to the traffic flow direction, as normal, or alongside the traffic flow, on the rib-line. In both cases, only one, or the two nearside tyres, would be detected, which could affect the classification and speed estimation. In addition, in the second configuration, the risk of the tubes being detached from the pavement due to traffic (and especially trucks) would be higher. Traffic management would be required for the installation and maintenance of pneumatic tubes (closure of the nearside traffic lane).

2.2.3 Piezoelectic

These sensors convert kinetic energy to electrical, generating a voltage when subjected to mechanical impact or vibration. The voltage is proportional to the vehicle weight [11]. Piezoelectric sensors can also classify vehicles by axle count and axle spacing and measure vehicle speed, when multiple sensors are deployed. Piezo-electric sensors can either be imbedded in the roadway, which requires cutting into the pavement surface, or placed on the road surface [13]. An advantage of this technology is the differentiation of individual vehicles axles with high precision. However, the accuracy of sensors is subject to pavement temperature and vehicle speed. As with pneumatic tubes, they can be displaced if on the road surface, while these can also fail due to poor road surface [11].

2.2.4 Magnetic

Magnetic sensors indicate the presence of a metallic object by the disruption it causes in an induced (active) or natural (passive) magnetic field [15]. The vehicle detection criterion is for the voltage to exceed a predetermined threshold. In order for the sensor to detect the change in the magnetic field, it must be relatively close to the vehicles; thus it is normally installed under or on top of the pavement. Magnetic sensors can be used to collect count, speed, and classification data; however, in operating conditions the sensors have difficulty differentiating between closely spaced vehicles [10, 13] and generally cannot detect the perimeter of a vehicle accurately, which is a requirement for this study. An advantage of the magnetic detectors in comparison to the inductive loops is that they cause less disruption on the road as they cover a smaller area. Also, they are less sensitive to stresses of traffic [11].

2.3 Examples of non-intrusive technologies

2.3.1 Infrared

There are two types of infrared technology: active and passive. The former is a device emitting a laser beam at the road surface, measuring the time for the reflected signal to return. The transmitted beam is interrupted by the vehicles, thus the reduction in time indicates this presence. The mounting position for active infrared sensors can vary from over the lane to roadside. Active infrared sensors can potentially provide information on the presence, the volume, the length, the speed and the number of axles. If the laser wavelength is between 400nm and 700nm, the beam is visible to the human eye and the sensor is called visible red light. The second infrared sensor type (passive) does not emit energy of its own and detects a vehicle by measuring infrared energy radiating from the detection zone. The infrared energy naturally emanating from the road surface is compared to the energy radiating when a vehicle is present. Passive infrared detectors are typically mounted over the traffic lane (e.g. on a gantry or bridge) or alternatively on a pole at the roadside. Both active and passive infrared devices can be used to record count, speed, and classification data and work well under day and night conditions. The main drawbacks are the performance during bad weather, and limited lane coverage [8, 10, 13].

2.3.2 Radar

Radar (RAdio Detection And Ranging) technology detects distant objects and is able to determine their position and speed. With vehicle detection, a device transmits high frequency radio waves at the roadway to determine the time delay of the return signal, thereby calculating the distance to the detected vehicle. In opposition to magnetic sensors, radar can also detect stationary vehicles, while at the same time, it can provide, if preferable, all the vehicle information per section of the detection area. An advantage of the radar is its insensitivity to inclement weather conditions and its capability to operate during day and night. [8, 13]. The radar sensor may be mounted over the carriageway (for single-lane monitoring) or at the side, off the hard-shoulder (for detection across several lanes). Side-mounted radars provide data corresponding to several traffic lanes, though generally not as accurately as in the over-looking position. However, side-mounted radars have also been used for single-lane detection [8].

2.3.3 Ultrasonic

The ultrasonic sensors transmit sound waves at a selected frequency between 20 and 65 kHz, to detect vehicles by measuring the time for the signal to return to the device. The preferred configurations for presence sensors are downward and side viewing, while for speed-measuring sensors is forward-looking. The transducers in both presence and speed-measuring devices convert the sonic energy received back into electrical energy that is then processed. Even though the implementation cost is relatively low, a disadvantage of the ultrasonic sensors is that they can be affected by inclement weather (e.g. low temperatures, snow) [8, 10].

3 Criteria for selection of technology

In order to select the most suitable technology for the hard-shoulder data collection, a series of criteria are applied.

3.1 Ability to collect data required

First and foremost, the equipment selected should be able to collect the data required as accurately as possible. Two potential limitations are the influence of vehicle speed and weather conditions. The technology selected must be effective in high speed conditions (the speed limit for general traffic on UK motorways is 70mph (112km/h) and 56mph for trucks (90km/h) [16]. Other potential issues are vehicles in close proximity, which might not be accurately classified as they are not always recognised as two or more separate vehicles, and stationary or slow-moving vehicles, which cannot be recorded by some technologies.

In terms of the environmental conditions, the performance of some types of technologies is influenced by weather events, such as fog, heavy rain and sub-zero temperatures, all of which are often encountered in the area of study. This also includes the detection of dark objects, which, depending on the abilities of the equipment, may be limited.

3.2 Cost

The overall cost of the use of equipment, which influences which type is used, includes the following:

- ***Procurement***: the cost of purchasing/renting the equipment, as well as all the accompanying elements (e.g. data logger, power supply establishment of internet connection for remote data collection).
- ***Installation***: the cost of the equipment to be deployed on the network. It includes the number of man-hours, the cost for traffic management (e.g. lane closure) and – if required and the possible interventions to the pavement or the existing infrastructure (e.g. gantries, lighting columns) that need to take place, especially if the technology is intrusive.
- ***Operation***: the cost of the energy consumed by the system and the cost for actions required during operation (e.g. manual data collection, systematic cleaning of the equipment).

- ***Maintenance***: this can be divided into the routine and emergency costs; it is the cost (including man-hours) for inspecting and repairing, as well as the cost of any traffic management requirements.
- ***Replacement/ Complete removal***: this cost depends on the actions required and the possible repairing that the road or the surrounding infrastructure might need, as, for example, in the case of inductive loops.

3.3 Installation, operation and maintenance requirements

It is desirable to have minimum installation, operation and maintenance requirements, as this reduces, apart from the cost, the risk to operatives and disruption for road users. For this, side-fire mounting is preferred to over-head as it is simpler to install (no lane closures required). In this context, it is generally preferable for the equipment to be non-intrusive. This means that it causes minimum disruption to normal traffic and the road. If non-intrusive, the equipment is also portable. This is a major advantage in cases that it is necessary to collect data from several locations and there are financial constraints at the same time (See Table 2).

Table 2. Equipment attributes desirable to the road users and the operator.

	INSTALLATION	OPERATION - MAINTENANCE
ROAD USER	Safe installation No lane closure or speed restrictions Minimum disruption	Safe operation and maintenance No distraction to drivers
MOTORWAY OPERATOR	Minimum time on the network for safety and cost Minimum disruption to the public as a good service should be provided No lane closure or Traffic Management to be installed Non-intrusive and/or portable Use of existing infrastructure as much as possible	Minimum maintenance required Reliability (minimum cost for inspection and repairs) Remote data collection Energy efficiency

3.4 Health, safety and security

For equipment to be installed and to operate on the network, health and safety requirements must be met. Generally, when a new piece of equipment is installed, a risk assessment and method statement are prepared to recognise and quantify the risks, mitigate or eliminate them and to determine a safe manner to carry out the installation and ongoing maintenance. Competence is key for health and safety for all phases and training is undertaken if required.

3.5 Overall

Overall, it is preferable that the equipment is transferable, i.e. it is possible to move it to another location under different conditions, as it gives the ability to collect data from a greater variety of locations. In addition, if the equipment has been used widely in the past, it means that it should be more reliable and any problems that might appear, as well as the limitations, are generally known. On the contrary, the use of a more contemporary system may offer a better perspective for alternative future uses.

4 Selection of implementation sites

In cases where it is not feasible to continuously monitor an area for incursions, mainly due to cost constraints, the sub-sections monitored should be carefully selected in order to cover an extensive variety of conditions, in terms of road construction characteristics (slope, curvature, hard-shoulder/main carriageway lane width, pavement type, street lighting, etc.) and other conditions, if these are known to change significantly (e.g. traffic volume, vehicle classification proportion). Proximity to a junction may also affect driving behaviour. In addition, the resources available on-site are investigated. These include power supply from existing electric cabinets, existing infrastructure that can be used for mounting the equipment (e.g. bridges, gantries), vehicle restraint system (VRS) which provides safer conditions for installation, maintenance and operation. It is also necessary to comply with health and safety legislation and the specification requirements of the Highways England in terms of installing new equipment on the motorway network, including the following:

- ***Structural Review***: A review of an individual or a group of structure (e.g. a bridge or a gantry) to confirm the load carrying capacity. This is conducted when the need arises, such as the installation on additional equipment on the structure, which increases the operational load [17].
- ***Technical Approval***: The submission of a Proposal, the acceptance of which confirms that the design, assessment, specification or construction works complies with the agreed design and specification certificates [18].
- ***VRS Length of Need***: That is the total minimum length of full height, full containment VRS as required in advance of, alongside, and after a hazard to protect this hazard, plus the additional lengths that are declared by the manufacturer to ensure full containment. Thus, any new equipment installed should not affect the VRS’ functionality in case of an impact [19].
- ***Working Width***: This is the maximum lateral distance between any part of the barrier and the maximum dynamic position of it. If the vehicle body deforms around the road VRS so that the latter cannot be used for the purpose of measuring the working width, the maximum lateral position of any part of the vehicle is taken as an alternative. The working width need to remain clear from any installations [19].
- ***Structure Free Zone***: This is a buffer zone adjacent to the paved carriageway and beneath a Structure that reduces the risk of errant vehicle impacts by providing an appropriate value of headroom [20].

- ***VRS Set-back***: Obstructions immediately adjacent to the edge of the paved carriageway result in drivers reducing speed and positioning their vehicles away from the obstruction. The purpose of the set-back is to provide a lateral distance between the VRS and the carriageway which reduces the effect of the safety barrier on driver behaviour and shyness. Any relaxations must consider the effects on the ability of occupants of stopped vehicles to leave via the nearside doors and the possibility of increased risk due to parking closer to live traffic [20].

5 Potential hard-shoulder incursions monitoring systems

After a range of sensors that can be altered to accommodate the study's needs are taken into consideration and the implementation sites are investigated, two potential solutions are suggested: a laser- and a radar-based system. The former is more flexible and easily transferable, while the latter has the potential to provide more detailed information.

5.1 Laser-based system

This system comprises of the laser sensors, the data logger and power supply. The laser sensor selected is provided by Micro-Epsilon (ILR1030-15), and has the ability to detect dark objects at a sufficient distance and a measuring frequency high enough to capture high-speed objects (Fig. 3) [21]. The sensors, while mounted at the side of the motorway pointing towards it perpendicularly, are measuring the distance to the overpassing vehicles. Due to the small size of the sensors (55x26x102mm – 90grams), they are not considered a risk to road users. As the laser is class 2, it poses no risk in case of eye contact. The sensors are placed inside a standard motorway marker post and are mounted to the rear of the VRS. The marker posts where the laser sensors are installed are additional to the existing ones. The sensors aim at an approximate height of 600mm above the carriageway at the outside edge of the rib-line and are levelled when installed.

Campbell Scientific provides a suitable data logger, also of a small size (241x104x51mm – 0.7kg), to store data from up to three laser sensors (Fig. 4) [22]. The logger has the ability to store data every 10-1 seconds, which allows the detection vehicles travelling at a speed of 40m/s or 150kph (90mph). Using the software provided with the data logger, the device is programmed so as whenever a vehicle crosses the rib-line, the measurement is recorded. The system can be powered either by using a battery, or by connection to the mains (where electric cabinets are present). The laser sensors are connected to and powered via the data logger. In order to protect the cables from damage the cables are carried in ducting.

5.2 Radar-based system

The alternative suggested method that can provide more detail is radar, which can monitor a continuous section of the motorway. A potential solution is provided by NavTech Radar [23]. The radar sensor is installed at the side of the motorway, while the mounting height can vary between 2m and 8m. For the hard-shoulder monitoring, a minimum height of 2m could be applied. However, to ensure security of the equipment, a mounting height of at least 3m is preferred. The higher the radar is mounted, the longer distance it can cover, whilst the blind area underneath the radar increases. The radar sensors are positioned to provide the optimum ‘line of sight’. In order to check what can be seen by the radar one has to stand at ground level where the radar is mounted, or ideally, at the height of the radar. Whatever is visible to a person is also visible to the radar. Street furniture, such as lamp posts, can create visual obstacles to the radar, especially further away where they appear to be closer together. In a straight line the radar can detect a person located between 20 and 350m away, depending on the road geometry and mounting height.

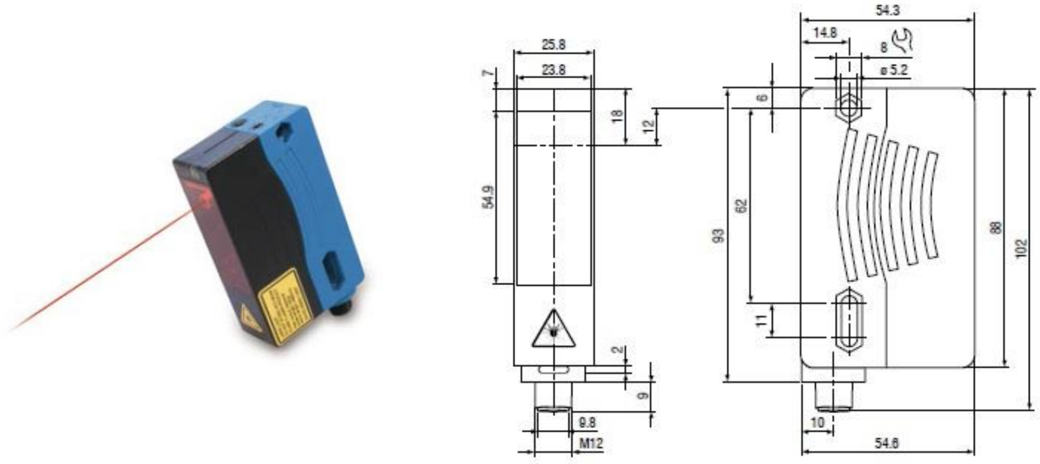

Figure 3. ILR1030-15 Laser sensor by Micro-Epsilon and dimensions (Source : Micro-Epsilon)

Figure 4. CR800 data logger (Source: Campbell Scientific)

The radar sensor may be mounted on dedicated posts, or various other structures – such as walls and gantries – using brackets. It is fitted to a plate on top of the post or the bracket using nuts and bolts which allows the tilt adjustment (levelling). On the M1-A1 Link Road, there are a series of structures that could be used for the radar mounting, such as A-Frame concrete gantries, bridges and variable message signs (VMS). While following the requirements of Highways England in the UK, several mounting solutions are investigated:

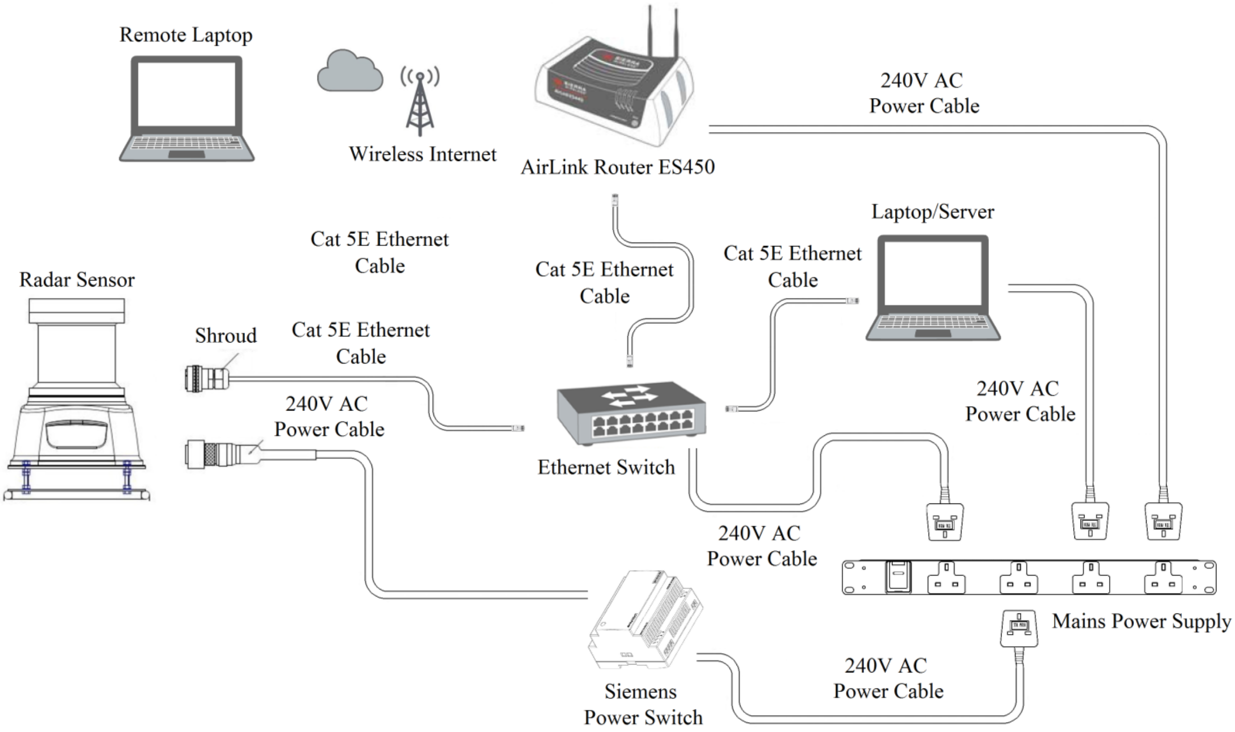

Figure 5. Set up of all the components of the radar system. (Source: P. Michalaki, created using NavTech Radar, Siemens and Sierra Wireless drawings)

- **Custom-made metal bracket**: The bracket can be installed either at the side of an A-Frame gantry support (by drilling and fixing into the concrete) or on its horizontal beam. The main advantages of the metal bracket are the relatively small size, which would not be a distraction to the drivers, and the low manufacturing cost. However, this solution is intrusive to the gantry, would require rectification afterwards, and a full design would be required, which significantly increases the cost. In addition, specialist installation resources and traffic management would be required for the installation of the metal bracket (closure of the hard-shoulder and the nearside traffic lane) resulting in higher disruption for the road user and also higher costs.
- **Pole**: The manufacturing cost for a pole is considerably higher than that for a bracket and its installation would also require disruptive traffic management, further increasing the cost.
- **Trailer Mast System**: A trailer system that can be used for mounting the radar sensor is also considered. The approximate dimensions of the trailer are 5.0x2.0x2.0m and the

approximate weight 500kg. The extended height can reach up to 15m. Even though the trailer could operate independently power-wise (solar power facility), which provides more flexibility, its size considerably restricts the locations where it can be used. This solution has higher maintenance requirements as well as certifications for its safety prior to the transfer.

- **Scaffold**: A scaffold is a temporary structure that can provide a stable base for the radar sensor. This is the solution considered the most suitable for this installation. The base plate is fastened to the scaffold and the radar sensor is positioned on top. The advantage of using a scaffold for this purpose is the non-intrusiveness to the existing structures on the network. In addition, the scaffold is set up ‘around’ a concrete gantry, thus the structure does not carry any additional weight, but does provide added restraint. In order for the scaffold to be installed, a hard-shoulder closure is required. After the scaffold is set up and the desired height is ensured (around 3.50m) using a simple distance measurement laser, the base plate is secured on top of the scaffold and the radar installed and levelled so it is parallel to the motorway surface. The levelling is achieved by fine adjustment of the nuts and bolts of the base plate. The base plate is first levelled to 0° and then adjusted according to the motorway slope. After installation access to the scaffold is prohibited to prevent unauthorised use or tampering with the equipment.

Each radar sensor requires a power and data connection via an Ethernet cable. Remote access minimises the necessity for site visits. In order to setup the radar system, several additional components are required. Fig. 5 shows all the connections of the radar system.

- **Power supply**: The radar uses 24V DC voltage and is powered via a transformer from the 240V AC mains (electric cabinet on-site). The power cable is provided with a military specification connector for the sensor connection and a bare end at the switch connection [24].
- **Ethernet connection**: An Ethernet cable is connected to the sensor for data transfer. A military specification shroud ensures a suitable environmentally protected network connection. At the other end, the Ethernet cable is connected to an Ethernet switch, which is also powered via the mains supply.
- **Laptop/Server connection**: A laptop or server is connected to the radar via the Ethernet switch. All components of the radar’s software are installed and running constantly on this device, which is required to have certain specifications and is selected accordingly.
- **Router connection**: In order to have remote access to the laptop/server on-site, a router connection is set up. The IP addresses of all components (router, router’s SIM card, on-site laptop/server, remote laptop) are synchronised for the system to function. In order to connect remotely to the laptop/server on-site, remote access software is used [25].

6 Conclusions

In this paper, the safety issue of motorway hard-shoulder incursions is approached. Since little is known about how these accidental movements occur, it is crucial to identify methods to monitor them so they can be further investigated. With no working or similar modifiable system available, alternative vehicle detection methods are considered. A review of intrusive and non-intrusive devices provided the advantages and disadvantages of each technology.

Looking at the practical whole life process, from procurement and deployment to operation and removal, the considerations in order to employ the most suitable systems were described including basic criteria for equipment and site selection, such as safety, ease of deployment and cost. Based on these factors, two potential systems, a laser-based and a radar-based are suggested. Further research on field tests is being conducted in order to fully evaluate the suitability of each system and gain more feedback on the system parameters and performance.

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